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# THEORETICAL INVESTIGATIONS OF THE PROPERTIES OF OBLIQUE DETONATION WAVES

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Philip 'F' Gibber

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Lieutenant, United States Navy

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE
IN
AERONAUTICAL ENGINEERING

United States Naval Postgraduate School Monterey, California

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bу

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from the

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#### ABSTRACT

One method of solving the problem of burning or combustion at supersonic speed is by combusting in a stationary detonation wave. Stabilization of a detonation wave has been recently accomplished and is reproducible, but only in laboratory type apparatus.

Using two-dimensional steady flow, perfect gas theory, this paper provides solutions for the changes in properties that may be expected across any oblique detonation wave.

Equations are established and solved using the Control Data Corporation 1604 digital computer of the U. S. Naval Postgraduate School, Monterey, California, for different values of specific heat ratio, initial Mach number, a function of the flow deflection angle, and the amount of heat added in the detonation. The results appear in tabular form and for several specific values of Mach number and heat addition in graphical form. An example of use of the data is shown with reference to a ramjet engine operating with a stationary detonation wave for the combustion process.

The author wishes to express his sincere appreciation to Professor Michael H. Vavra for his encouragement, supervision, and patience during the period of this work.

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#### TALLE OF SYMBOLS

### Symbol

- a Acoustic velocity
- a Critical acoustic velocity
- M Mach number
- $M_1^*$  Velocity ratio,  $V_1/a_1^*$
- $M_2^*$  Velocity ratio,  $V_2/a_2^*$
- $M_{2u}^{*}$  Velocity ratio,  $u/a_{2}^{*}$
- \* Velocity Ratio, v/a<sub>2</sub>
- p Static pressure
  - P<sub>T</sub> Total pressure
  - PR21 Pressure ratio, p<sub>2</sub>/p<sub>1</sub>
  - PTR21 Total pressure ratio, p<sub>T2</sub>/p<sub>T1</sub>
  - R Universal gas constant
  - T Static temperature (° Rankine)
  - $T_{\mathrm{T}}$  Total temperature (° Rankine)
  - TR21 Temperature ratio,  $T_2/T_1$
  - u Horizontal velocity component of  $V_2$
  - v Vertical Velocity component of  $V_2$
  - V Velocity
  - х М<sub>2 ь</sub>
  - y M<sub>2</sub>v
  - $\delta$  Heat addition parameter,  $({ t T}_{ t T2}/{ t T}_{ t T1})^{1/2}$
  - Y Specific heat ratio
  - P Density
  - T Detonation (or shock) wave angle
  - $\Theta$  Flow deflection angle

#### TABLE OF SYMBOLS

### Subscripts

- l Before Detonation Wave
- 2 After Detonation Wave
- max Maximum
- min Minimum
- n Normal
- t Tangential
  - T Total (stagnation)
  - u In u direction
- v In v direction

#### CHAFIER I

#### INTRODUCTION

A detonation wave is a phenomenon which may occur as a result of a combustion process. The difference between a detonation wave and an ordinary deflagration wave or burning is that a detonation wave travels at supersonic velocity whereas a deflagration wave travels at subsonic velocity. Much has been written about detonation waves. 1, 2, 3, 4

Recently stationary normal detonation waves have been produced and maintained in a special supersonic wind tunnel.

This thesis evaluates the downstream properties of a plane oblique stationary detonation wave as a function of the initial Mach number, flow deflection angle, and the amount of heat added in the detonation wave. The heat added is represented by a parameter  $\delta$ , the ratio of the total (stagnation) temperature after the detonation wave, to the total temperature prior to detonation. In addition, properties after the detonation wave are calculated for three values of the specific heat ratio  $\delta$ , namely 1.2, 1.3, and 1.4.

Due to the complexities of establishing equations for actual flows for which solutions can be found, several basic assumptions have been made in the calculations. It is assumed that:

- 1) The flow is uniform and steady.
- 2) The gas to be burned is an ideal gas, i.e., the equation of state

$$pv = RT$$

defines the state of the fluid at any time.

- 3) The friction between the fluid and the wall is considered negligible, or a non-viscous fluid is assumed.
- 4) The entire process is considered to take place in an isolated system. The process is assumed to be adiabatic except for the addition of heat in the detonation.
- 5) Transport properties such as internal heat transfer by radiation and conduction are neglected.
- 6) The composition of the fluid and the specific heats are unchanged through the detonation wave, i.e.,

  2 and the universal gas constant, R, remain constant.

Assumption 6) places the most severe restrictions on the applications of the results, but without these simplifications, the equations would become considerably more complicated if at all solvable.

If it proves possible to stabilize detonation waves in a practical manner, several possibilities for their use are imaginable; 1) use of the detonation as a combustion system for a ramjet, and 2) use of the detonation to provide underwing heating as a lift augmentation device or even as a means of primary propulsion.

There are several advantages of detonation wave combustion over conventional combustion in a ramjet. At the present state of the art, velocities of fuelair mixtures entering a combustion chamber must be subsonic in order to achieve stable burning. This dictates deceleration of the incoming supersonic flow through a diffuser to subsonic speed. In the combustion chamber a flameholder is necessary to insure continuous combustion.

A ramjet operating with a standing detonation wave where the combustion takes place could be smaller and of simpler design. An inlet duct would be necessary to inject and mix fuel into the flow. The supersonic stream could be detonated in a normal detonation wave by spontaneous combustion if temperatures are high enough, or by an electric spark. The velocity after the detonation would be subsonic and would then be accelerated by passing through a converging diverging nozzle. A simplified schematic of such an engine is shown in Fig. 1.

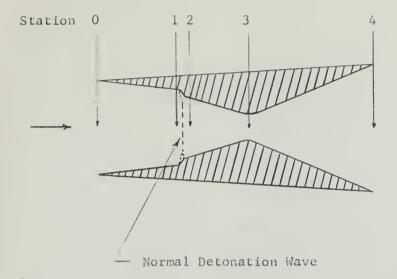


Fig. 1 Schematic of a Detonation Wave Ramjet Engine

The formation of the normal detonation wave between stations 1 and 2 near the wedge at the walls is postulated since such a near normal detonation wave has been stabilized, observed and reproduced<sup>5</sup>.

Fig. 2 shows an example of a ramjet engine using an oblique detonation wave for a combustion process. In this engine fuel is mixed with a supersonic incoming stream. An oblique detonation wave is formed at a conically pointed body. After the detonation wave the flow is of sonic velocity or greater and is then expanded to higher velocity.

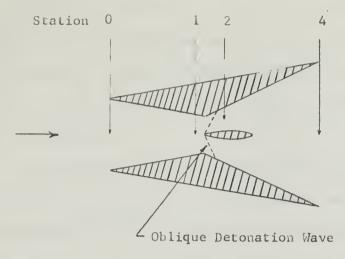


Fig. 2 Schematic of a Detonation Wave Ramjet

Fig. 3 is a concept of Sargent and Gross<sup>6</sup>. In Fig. 3 a free stream of Mach 6 is decelerated to Mach 4.0 and is detonated such that the products of detonation have sonic velocity. This flow is then accelerated in a nozzle.

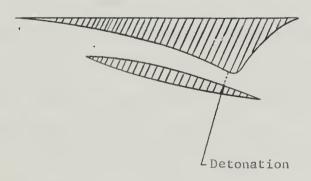


Fig. 3 Schematic of a Detonation Wave Ramjet Engine

It has been theorized, that the conventional subsonic burning ramjet engine will have a greater efficiency up to Mach numbers of 7 to 8. Above Mach 8 the efficiency of the supersonic compustion ramjet will be greater.

Experiments in supersonic combustion have been conducted with successful results without using detonation. 8,9,10,11 Aluminum borohydrige was burned under the surface of a wing and a flat plate in a wind tunnel in the Mach 2.4 to 3.0 range. It was found that underwing heating increased the static pressure in the heated area. This pressure increase resulted in an increased lift and lift-drag ratio. The added lift could be used to increase the rate of climb, decrease the wing area needed, or if intermittent burning is considered, as a means of controlling or increasing the maneuverability of a missile or ramjet at high altitude. With a specially designed airfoil underwing heating provides a method of propulsion 10 as shown in Fig. 4. The similarity with Fig. 3 may be noted.

A detonation wave may be a possible method of adding the heat necessary for underwing heating.

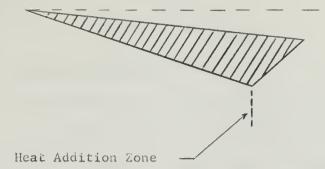


Fig. 4 Schematic of Supersonic Burning Under a Wing

#### CHAPTER II

#### ANALYSIS OF PROBLEM

### 1. Classical Shock Polar.

The solution to the problem of finding the properties of an oblique detonation wave is made along lines similar to those used for establishing the classical shock polar. The shock polar is used for determining properties after an oblique shock wave if no heat is added to the system. Fig. 5 depicts a wedge of flow deflection angle  $\vartheta$  in a supersonic stream of velocity  $V_1$ . An oblique shock wave forms at an angle  $\vartheta$ , at

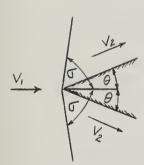


Fig. 5 A Wedge in a Supersonic Flow

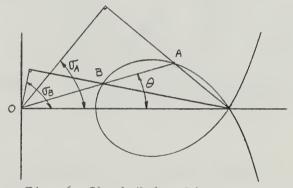


Fig. 6 Shock Polar Diagram

the apex of the wedge. Behind the shock wave the velocity  $\mathbf{V}_2$ , is shown at an angle  $\theta$ . For a given  $\mathbf{V}_1$  Fig. 6 represents a typical shock polar diagram for a flow such as that of Fig. 5. For a flow deflection angle  $\theta$ , OA and OB represent the two possible values of  $\mathbf{V}_2$ . The ordinate and abscissa represent

the vertical and horizontal components of  $V_2$ , and  $\mathcal{T}_A$  and  $\mathcal{T}_B$  the possible shock wave angles. Fig. 5 and Fig. 6 are both symmetrical about the horizontal axis.

#### 2. Detonation Polar.

If the shock in Fig. 5 is not considered to occur at constant total temperature or if the shock may be considered a detonation, the velocities of the fluid may be shown as in Fig. 7 and Fig. 8. Fig. 7 shows

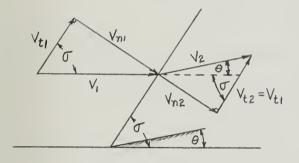


Fig. 7 Velocities across a Detonation Wave

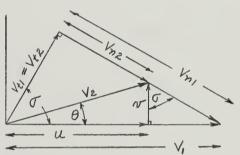


Fig. 8 Velocities across a Detonation Wave Superimposed

the velocities and their components as they would appear relative to the detonation wave and Fig. 8 shows them superimposed. Due to the symmetry about the horizontal axis only half the flow is shown. For such a detonation wave the law of conservation of mass can be applied normal to the detonation wave if it is assumed that the entire combustion takes place in the detonation wave and that the detonation wave is infinitesimally thin. Thus

$$\rho_i V_{ni} = \rho_2 V_{n2} \tag{1}$$

Application of the conservation of momentum parallel to the detonation wave shows that the tangential components of the velocities, that is, the components parallel to the detonation wave, must be the same on both sides of the wave or

$$v_{r1} = v_{r2}$$

Likewise the conservation of momentum applied normal to the detonation wave can be written

$$p_1 + \rho_1 V_{n1}^2 = p_2 + \rho_2 V_{n2}^2$$
 (2)

Dividing Eq. 2 by Eq. 1 and rearranging

$$\frac{p_2}{\rho_2 V_{n2}} - \frac{p_1}{\rho_1 V_{n1}} = V_{n1} - V_{n2}$$
 (3)

From

$$a^2 = \gamma RT$$

and the equation of state

$$\frac{\gamma p}{\varrho} = RT = \frac{a^2}{\gamma} \tag{4}$$

substitution into Eq. 3, for the appropriate subscripted values of  $\frac{\mathcal{P}}{\rho}$  and multiplying through by  $\mathbf{V}_{\text{nl}}$  , gives

$$\frac{a_{2}^{2} V_{ni}}{\gamma V_{n2}} - \frac{a_{i}^{2}}{\gamma} = V_{ni} (V_{ni} - V_{n2})$$
 (5)

From Fig. 6

$$\sin \sigma = \frac{V_{n_1}}{V_1} = \frac{V_1 - u}{V_{n_1} - V_{n_2}}$$

and

$$V_{n_{I}}\left(V_{n_{I}}-V_{n_{2}}\right)=V_{I}\left(V_{I}-\mathcal{U}\right) \tag{6}$$

or

$$\frac{V_{n2}}{V_{ni}} = I - \frac{V_{i}(V_{i} - u)}{V_{ni}^{2}}$$
 (7)

From Fig. 8

$$\tan \sigma = \frac{V_{1-u}}{v} = \frac{V_{n_1}}{V_t} = \frac{V_{n_1}}{\sqrt{V_1^2 - V_{n_1}^2}}$$

and

$$V_{n_1}^2 v^2 = (V_1 - u)^2 (V_1^2 - V_{n_1}^2)$$

or

$$V_{n_{1}}^{2} v^{2} = V_{i}^{2} (V_{i} - u)^{2} - V_{n_{1}}^{2} (V_{i} - u)^{2}$$

and

$$\frac{1}{V_{ni}^{2}} = \frac{v^{2} + (v_{i} - u)^{2}}{v_{i}^{2}(v_{i} - u)^{2}}$$
 (8)

Substituting Eq. 8 into the right side of Eq. 7

$$\frac{V_{n2}}{V_{nl}} = \frac{u(V_l - u) - v^2}{V_l(V_l - u)}$$

or

$$\frac{\forall_{n_1}}{\forall_{n_2}} = \frac{\forall_i (\forall_i - u)}{\cup (\forall_i - u) - v^2}$$
(9)

Substituting Eq. (9) and Eq. (6) into Eq. (5)

$$a_{2}^{2}\left[\frac{\sqrt{(V_{i}-u)}}{u(V_{i}-u)-v^{2}}-a_{i}^{2}=V_{i}(V_{i}-u)\right]$$
(10)

In order to correlate the quantity of heat added in the detonation wave to the velocities and acoustic velocities before and after the detonation wave, a transformation to a new reference system is desirable. Considering the flow before the detonation wave as having originated in a reservoir, then for a given reservoir condition the relation between the acoustic velocity  $a_0$ , of the fluid in the reservoir and the critical acoustic velocity  $a^*$  for an isentropic process is

$$a^* = \frac{2}{\gamma + 1} a^2$$

The relation between reservoir conditions and conditions at any point in an isentropic flow is

$$\frac{a^2}{\gamma - 1} + \frac{V^2}{2} = \frac{a^2}{\gamma - 1}$$

where a and V refer to any point in the flow. Elimination of  $a_0$  from these equations results in

a relation between a, a\*, and V , namely

$$a^{2} = \left(\frac{\gamma_{+/}}{2}\right) a^{*2} - \left(\frac{\gamma_{-/}}{2}\right) V^{2} \tag{11}$$

Using Eq. 11 with proper subscripts,  $a_1$  and  $a_2$  can be eliminated from Eq. 10 and

$$\left[ \left( \frac{\gamma + 1}{2} \right) d_{z}^{*2} - \left( \frac{\gamma - 1}{2} \right) V_{z}^{2} \right] \left[ \frac{V_{i} \left( V_{i} - u \right)}{u \left( V_{i} - u \right) - v^{2}} \right] - \left[ \left( \frac{\gamma + 1}{2} \right) d_{i}^{*2} - \left( \frac{\gamma - 1}{2} \right) V_{i}^{2} \right] \\
= V_{i} \left( V_{i} - u \right) \gamma \tag{12}$$

with

$$V_2^2 = u^2 + v^2 \tag{13}$$

The quantity  $V_2$  may be eliminated from Eq. 12. Substituting Eq. 12 into Eq. 13 and expanding yields

$$\begin{split} & \left[ (\gamma + 1) \, a_2^{*2} - (\gamma - 1) (\, u^2 + v^{-2}) \right] \left[ \, V_i \, (\, V_i - u) \right] \\ & - \left[ (\gamma + 1) a_i^{*2} - (\gamma - 1) \, V_i^{\, 2} \right] \left[ \, u_i \, (\, V_i - u_i) - v^{\, 2} \right] \\ & = \, 2 \, V_i \, \gamma \, (\, V_i - u_i) \, \left[ \, u_i \, (\, V_i - u_i) - v^{\, 2} \right] \end{split}$$

or

$$\begin{split} & \left[ \left( \gamma + 1 \right) a_{z}^{*2} V_{i} \left( V_{i} - u \right) \right] - \left[ \left( \gamma - 1 \right) u^{2} V_{i} \left( V_{i} - u \right) \right] \\ & - \left[ \left( \gamma - 1 \right) v^{2} V_{i} \left( V_{i} - u \right) \right] - \left[ \left( \gamma + 1 \right) a_{i}^{*2} u \left( V_{i} - u \right) \right] \\ & + \left[ \left( \gamma + 1 \right) a_{i}^{*2} v^{2} \right] + \left[ \left( \gamma - 1 \right) V_{i}^{2} u \left( V_{i} - u \right) \right] - \left[ \left( \gamma - 1 \right) V_{i}^{2} v^{2} \right] \\ & - \left[ 2 \, \gamma \, V_{i} u \left( V_{i} - u \right)^{2} \right] + \left[ 2 \, \gamma \, V_{i} \left( V_{i} - u \right) v^{2} \right] = 0 \end{split}$$

Solvin, for v

$$v^{2} = \frac{(V_{1} - u)[(y+1)d_{2}^{*2}V_{1} - (y-1)u^{2}V_{1} - (y+1)d_{1}^{*2}u + (y-1)V_{1}^{2}u - 2yV_{1}u(V_{1} - u)]}{(y-1)V_{1}(y-1) - (y+1)d_{1}^{*2} + (y-1)V_{1}^{2} - 2yV_{1}(V_{1} - u)}$$

$$V = \frac{(V_1 - u) \left[ (\chi + 1) \left\{ a_2^* V_1 - a_1^* u - V_1 u (V_1 - u) \right\} \right]}{- (\chi + 1) a_1^* - 2 V_1^2 + u V_1 (\chi + 1)}$$

$$v^{2} = \frac{\left(V_{i} - u\right)^{2} \left[u - \frac{\left(a_{2}^{*} V_{i} - a_{i}^{*} u\right)}{V_{i} \left(V_{i} - u\right)}\right]}{\frac{a_{i}^{*}}{V_{i}} + \left(\frac{2}{2H}\right)V_{i} - u}$$
(14)

It is customary and useful to express supersonic velocities by non-dimensional velocity ratios. These velocity ratios can be used to eliminate  $a_1^*$  and  $a_2^*$  as working parameters and simultaneously introduce the heat addition parameter  $\delta$ . To accomplish this let, by definition

$$M_{2v}^* \equiv \frac{v}{d_2^*} \tag{15}$$

$$M_{2u}^* = \frac{u}{a_2^*} \tag{16}$$

$$M_1^* = \frac{V_i}{a_i^*} \tag{17}$$

$$\delta = \frac{T_{72}}{T_{71}} \tag{18}$$

where the designation  $M^*$  means a velocity ratio based on a critical acoustic velocity of a fluid in a reservoir. The parameter  $\delta$  is a measure of the heat added by combustion during the detonation.

Assuming that the specific heats remain unchanged by the combustion,  $\delta$  is also proportional to the ratio of total enthalpies after and before the detonation wave.

With

$$a_{i}^{*2} = \left(\frac{2}{\gamma_{+1}}\right) a_{o}^{2} = \left(\frac{2}{\gamma_{+1}}\right) \gamma_{R} T_{\tau_{1}}$$

$$a_{z}^{*2} = \left(\frac{2}{\gamma_{+1}}\right) \gamma_{R} T_{\tau_{2}}$$

and

there is 
$$\frac{a_2^*}{a^{*2}} = \frac{T_{72}}{T_{72}} \equiv \delta^2 \tag{19}$$

Substitution of Eq. 15, Eq. 16, Eq. 17, and Eq. 19 into Eq. 14 yields the following series of equations

$$\frac{\sqrt{\frac{d_{1}^{*}}{d_{1}^{*}}} - \frac{ud_{2}^{*}}{d_{1}^{*}} - \frac{ud_{2}^{*}}{d_{2}^{*}}}{\sqrt{\frac{d_{2}^{*}}{d_{1}^{*}}} - \frac{d_{2}^{*}v_{1}\frac{d_{1}^{*}}{d_{1}^{*}} - d_{1}^{*}u\frac{d_{2}^{*}}{d_{2}^{*}}}{\sqrt{\frac{d_{1}^{*}}{d_{1}^{*}}\left(\sqrt{\frac{d_{1}^{*}}{d_{1}^{*}}} - u\frac{d_{2}^{*}}{d_{2}^{*}}\right)}}}{\frac{d_{2}^{*}}{d_{2}^{*}}} = \frac{\frac{d_{2}^{*}v_{1}}{d_{2}^{*}} - u\frac{d_{2}^{*}}{d_{2}^{*}}}{\sqrt{\frac{d_{1}^{*}}{d_{1}^{*}}\left(\sqrt{\frac{d_{1}^{*}}{d_{1}^{*}}} - u\frac{d_{2}^{*}}{d_{2}^{*}}\right)}}}{\frac{d_{2}^{*}}{v_{1}} + \left(\frac{2}{2+1}\right)v_{1}\frac{d_{1}^{*}}{d_{1}^{*}} - u\frac{d_{2}^{*}}{d_{2}^{*}}}{\sqrt{\frac{d_{1}^{*}}{d_{1}^{*}}} - u\frac{d_{2}^{*}}{d_{2}^{*}}}}$$

$$M_{2r}^{*} d_{2}^{*} = \frac{\left(M_{1}^{*} d_{1}^{*} - M_{2u}^{*} d_{2}^{*}\right) \left[M_{2u}^{*} d_{2}^{*} - \frac{\left(M_{1}^{*} d_{2}^{*} d_{1}^{*} - M_{2u}^{*} d_{1}^{*} d_{2}^{*}\right)}{M_{1}^{*} d_{1}^{*} \left(M_{1}^{*} d_{1}^{*} - M_{2u}^{*} d_{2}^{*}\right)}\right]}{\frac{d_{1}^{*}}{M_{1}^{*}} + \left(\frac{2}{2H}\right) M_{1}^{*} d_{1}^{*} - M_{2u}^{*} d_{2}^{*}$$

$$M_{zv}^{*2} = \frac{\left(\frac{M_{i}^{*} - M_{zu}^{*}}{\delta}\right)^{2} \left[M_{zu}^{*} \delta - \frac{\delta^{2} M_{i}^{*} - \delta M_{zu}^{*}}{M_{i}^{*} (M_{i}^{*} - \delta M_{zu}^{*})}\right]}{\frac{1}{M_{i}^{*}} + \left(\frac{2}{2H}\right) M_{i}^{*} - \delta M_{zu}^{*}}$$

$$M_{2v}^{*2} = \frac{\left(M_{i}^{*} - S M_{2u}^{*}\right)^{2} \left[M_{2u}^{*} - \frac{\left(S M_{i}^{*} - M_{2u}^{*}\right)}{M_{i}^{*} \left(M_{i}^{*} - S M_{2u}^{*}\right)}\right]}{S \left[\frac{1}{M_{i}^{*}} + \left(\frac{2}{3+1}\right) M_{i}^{*} - M_{2u}^{*}S\right]}$$

$$M_{2v}^{*} = \frac{\left(M_{i}^{*} - SM_{2u}^{*}\right) \left[M_{2u}^{*} \left(M_{i}^{*} - SM_{2u}^{*}\right) - \frac{\left(SM_{i}^{*} - M_{2u}^{*}\right)}{M_{i}^{*}}\right]}{S\left[\frac{1}{M_{i}^{*}} + \left(\frac{2}{\gamma H}\right)M_{i}^{*} - SM_{2u}^{*}\right]}$$
(20)

This equation is the basic relation between the properties ahead of and after the oblique detonation wave. Introducing

$$x = M_{2u}^{*}$$

$$y = M_{2v}^*$$

substitution yields

$$y^{2} = \frac{\left(M_{i}^{*} - \delta \chi\right) \left[\chi\left(M_{i}^{*} - \delta \chi\right) - \frac{\left(\delta M_{i}^{*} - \chi\right)}{M_{i}^{*}}\right]}{\delta \left[\frac{1}{M_{i}^{*}} + \left(\frac{2}{2+1}\right)M_{i}^{*} - \delta \chi\right]}$$
(20a)

In equation Eq. 20a y is given as a function of  $\delta$  ,  $M_1^*$  ,  $\forall$  , and x. When the heat addition parameter  $\delta$  is unity, i.e., if no heat is added, the equation reduces to that of the shock potar. When  $\delta$  is greater than unity, however, the curve of the equation has two non-intersecting branches. One part is an ellipselike curve which shall henceforth be called the loop branch. The other part has a range of y values from plus infinity to minus infinity for finite values of x. This part shall be referred to as the infinite branch. Typical examples of the graph of Eq. 20a for a given  $\delta$  and  $\delta$  are shown in Fig. 9 for values of  $\delta$  of unity and greater than unity.

The velocity ratio  $\text{M}_1^\star$  appears in Eq. 20a and also in later equations and calculations. A relation to transform  $\text{M}_1^\star$  to  $\text{M}_1$  and vice versa is useful and desirable. By definition

$$M_{\perp}^{\star} \equiv \frac{V_{I}}{\partial_{I}^{\star}} = M_{I} \frac{\partial_{I}}{\partial_{I}^{\star}} \tag{21}$$

and

$$M_1 \stackrel{*2}{=} M_1 \frac{2(a_1)}{a_1^*}^2$$

From Eq. 11

$$a_1^2 = \left(\frac{y_{+l}}{2}\right) \mathcal{Z}_{l}^{*2} - \left(\frac{y_{-l}}{2}\right) V_{l}^{2}$$

$$1 = \left(\frac{\gamma_{+1}}{2}\right)\left(\frac{\lambda_{1}^{*}}{\lambda_{1}}\right)^{2} - \left(\frac{\gamma_{-1}}{2}\right)M_{1}^{2}$$
 (22)

$$\left(\frac{\partial_{i}}{\partial_{i}^{*}}\right) = \frac{\gamma+1}{2+(\gamma-1)M_{i}^{2}}$$

Therefore

$$M_1^{*2} = \frac{M_1^{2}(\gamma+1)}{2+(\gamma-1)M_1^{2}} \tag{23}$$

and

$$M_1^2 = \frac{2M_*^{*2}}{(y+1)-(y-1)M_*^{*2}}$$
 (24)

Eq. 23 shows that as  $\rm M_1$  approaches an infinitely large value,  $\rm M_1^*$  approaches a finite limit of

$$M_1^* = \sqrt{\frac{\gamma+1}{\gamma-1}}$$

In particular, for  $\chi = 1.4$ 

$$M_1^* = \sqrt{6} = 2.4495$$

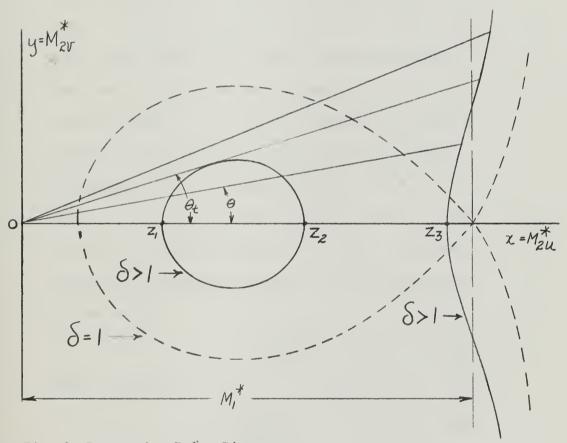


Fig. 9 Detonation Polar Diagram

Eq. 23 is shown in graphical form in Fig E-l in Appendix E.

### 3. Discussion of Detonation Polar Equation.

The general form of Eq. 20a is that of a cubic

$$y^2 = f(x^3)$$

Such a curve may have three values of x at which y is zero or at which the curve crosses the x axis. For given values of  $M_1^*$ ,  $\mathcal{S}$ , and  $\mathcal{Y}$  these zero values are fixed. The minimum and maximum values of x on the loop branch,  $Z_1$  and  $Z_2$  respectively on Fig. 9, are found by setting the right hand bracket of the numerator to zero. For heat addition,  $\mathcal{S} > 1$ , the values of x are always less than  $M_1^*$ . With no heat addition the maximum value of x is  $M_1^*$ . The general equation for finding the zeros of the loop branch may be reduced to

$$x = A \pm \sqrt{A^2 - 1}$$
 (25)

where A is defined by

$$A \equiv \frac{M_{,}^{*2} + I}{2 \delta M_{,}^{*}} \tag{26}$$

From Eq. 25 and Eq. 26 it is seen that there exists a maximum value of  $\delta$  or a maximum amount of heat which

can be added in the detonation wave for any given value of  $\text{M}_1^\star$ . When A of Eq. 26 is equal to unity the loop branch degenerates to a single point. At values less than unity the solution becomes imaginary and the loop branch disappears completely.  $\delta_{\text{max}}$ , the maximum value of  $\delta$ , is found from Eq. 26 for A = 1 by

$$\delta_{\text{max}} = \frac{M_i^{*2} + I}{2 M_i^{*}} \tag{27}$$

The third zero,  $\mathbf{Z}_3$  on Fig. 9, is found by equating the left hand bracket of the numerator to zero so that

$$x = \frac{M_i^*}{\delta}$$
 (28)

This value of x is also less than  $M_1^*$  for  $\delta > 1$ . When  $\delta = 1$ , x reaches a maximum equal to  $M_1^*$  and the points  $Z_2$  and  $Z_3$  coalesce. Eq. 27 and Eq. 28 show that for values of  $\delta > \delta_{max}$ , the infinite branch exists although the loop branch has disappeared.

A fourth value of interest is the value of x at which y becomes infinite, i.e., the value of x which makes the denominator of Eq. 20a zero. This is

$$x = \left[\frac{1}{M_{l}^{*}} + \left(\frac{2}{g+1}\right)M_{l}^{*}\right] \frac{1}{\delta}$$
 (29)

Eq. 29 gives the maximum possible value of x for any given X,  $M_1^*$ , and  $\delta$ , and may be  $\geq M_1^*$  depending upon the amount of heat added in the detonation wave.

In the shock polar of Fig. 6, OA represents the velocity  $V_2$  .  $\theta$  represents the flow deflection angle. In the detonation polar a position line, a line drawn from the origin (x = 0, y = 0) to any point on the detonation polar, represents a function of  ${ t V}_2$  and  ${ t \delta}$  .  $\theta$  remains the flow deflection angle. As can be seen in Fig. 9, there are three distinct cases and/or ranges of  $\theta$  . In the first case  $~\theta~$  varies from  $0^{\rm O}~$  to  $\theta_{\rm t}$  , the angle at which a position line is tangent to the loop branch. The second case is  $\theta = \theta_{+}$  , and in the third case  $\theta > \theta_{\rm r}$  . All three conditions exist in the shock polar also. A position line intersects the infinite branch once, twice, or not at all. In the shock polar the intersection with the infinite branch can be eliminated as a possible solution since this part of the curve corresponds to values of  $V_2$  greater than  $V_1$  . Such an increase in velocity across a shock wave would be accompanied by a decrease in entropy, a violation of the second law of thermodynamics.

In the detonation polar the intersection of a position line with the infinite branch also produces solutions inconsistent with the second law of thermodynamics. By definition

$$x = \frac{u}{d_2^*} \leq \frac{V_2}{d_2^*}$$

Across a detonation wave  $V_1 > V_2$  so that

$$x \stackrel{<}{=} \frac{V_2}{\partial_2^*} < \frac{V_1}{\partial_2^*} \tag{30}$$

By tautology, Eq. 19, and Eq. 17,

$$\frac{V_1}{a_2^*} = \frac{V_1}{a_2^*} \frac{a_2^*}{a_1^* \delta} = \frac{M_1^*}{\delta}$$

Substitution in Eq. 30 gives

$$x < \frac{M'_{\star}}{\delta} \tag{31}$$

Eq. 28 shows that the minimum value of x on the infinite branch is  $\frac{M_i^*}{\delta}$  or  $\frac{M_i^*}{\delta}$ 

$$x \stackrel{\geq}{=} \frac{M_i^*}{\delta} \tag{32}$$

Comparison of the inequalities of Eq. 31 and Eq. 32 show the infinite branch of the detonation polar to correspond to solutions where  ${\rm V_2 > V_1}$ . Thus the infinite branch is of no practical value for determining properties after an oblique detonation wave.

A position line generally intersects the loop branch of the detonation polar at two points, corresponding to weak and strong detonation waves. Each point determines the possible properties of the flow after the detonation wave. The values corresponding to points on the detonation polar are the principal subject of this thesis and

will be treated subsequently.

When  $\theta=\theta_{t}$ , the position line is tangent to the loop branch, and only one possible condition may exist after the detonation wave. Values of  $\theta>\theta_{t}$  correspond to a detached shock wave in the shock polar. Similarly for the detonation polar it may be theorized that a detached detonation wave would form for  $\theta>\theta_{t}$  but this occurrence would have to be verified by experimental evidence.

For the range  $\theta$  to  $\theta_t$ , using Eq. 20a as a basis for the conditions across a detonation wave, the properties of state after the detonation wave can be established.

# 4. Temperature Ratios.

By definition the total temperature ratio is

$$\frac{T_{T2}}{T_{T1}} \equiv \delta^2$$

The total temperature is related to the static temperature by

$$T_{T} = T \left[ I + \left( \frac{\gamma - I}{2} \right) M^{2} \right]$$
 (33)

For simplicity, let

$$D = 1 + \left(\frac{\sqrt[3]{2}}{2}\right) M^2 \tag{34}$$

hence,

$$T_T = TD$$

The static temperature ratio is therefore

$$\frac{T_2}{T_1} = \frac{T_{72} D_1}{T_{71} D_2} = S^2 \frac{D_1}{D_2}$$
 (35)

## 5. Pressure Ratios.

With

$$\frac{p_2}{p_1} = \frac{\rho_2 R T_2}{\rho_1 R T_1}$$

Eq. 35 gives

$$\frac{P_2}{P_1} = \delta^2 \frac{\rho_2 D_1}{\rho_1 D_2}$$

Using the density ratio of Eq. 1

$$\frac{\mathcal{P}_2}{\mathcal{P}_1} = \delta^2 \frac{V_{n1} D_1}{V_{n2} D_2}$$

From Eq. 9 the ratio of the velocities normal to the detonation wave is expressed by

$$\frac{p_2}{p_i} = \left[ \frac{V_i (V_i - u)}{u (V_i - u) - v^2} \right] \delta^2 \frac{D_i}{D_2}$$

By tautology, definition of Mach number, Eq. 19 and

$$\frac{d_2^2}{d_i^2} = \delta^2 \frac{D_i}{D_2}$$

there is

$$\frac{P_{z}}{P_{i}} = \delta^{2} \frac{D_{i}}{D_{z}} \left[ \frac{M_{i}^{2} a_{i}^{2} - M_{i} M_{2U} a_{i} a_{z}}{M_{i} M_{2U} a_{i} a_{z} - M_{2U}^{2} a_{z}^{2} - M_{2V}^{2} a_{z}^{2}} \right]$$

and

$$\frac{P_{2}}{P_{i}} = \delta^{2} \frac{D_{i}}{D_{2}} \left[ \frac{M_{i}^{2} - M_{i} M_{2u} \delta \left(\frac{D_{i}}{D_{2}}\right)^{1/2}}{M_{i} M_{2u} \delta \left(\frac{D_{i}}{D_{2}}\right)^{1/2} - M_{2}^{2} \delta^{2} \left(\frac{D_{i}}{D_{2}}\right)} \right]$$

The static pressure ratio can then be calculated from

$$\frac{\mathcal{P}_{z}}{\mathcal{P}_{i}} = \delta \left(\frac{D_{i}}{D_{z}}\right)^{\frac{1}{2}} \frac{M_{i}^{2} - M_{i} M_{zu} \delta \left(\frac{D_{i}}{D_{z}}\right)^{\frac{1}{2}}}{M_{i} M_{zu} - M_{z} \delta \left(\frac{D_{i}}{D_{z}}\right)^{\frac{1}{2}}}$$
(36)

or

$$\frac{\mathcal{P}_{2}}{\mathcal{P}_{i}} = \delta \left(\frac{D_{i}}{D_{2}}\right)^{1/2} \cdot \left[\frac{M_{i}^{2} - M_{i} M_{2} \cos \theta \delta \left(\frac{D_{i}}{D_{2}}\right)^{1/2}}{M_{i} M_{2} \cos \theta - M_{2}^{2} \delta \left(\frac{D_{i}}{D_{2}}\right)^{1/2}}\right]$$
(37)

The total pressure is related to the static pressure by

$$P_{\mathrm{T}} = p \left[ 1 + \left( \frac{\gamma - 1}{2} \right) M^{2} \right] = p D^{\frac{\gamma}{\beta - 1}}$$
(38)

and

$$\frac{P_{72}}{P_{71}} = \frac{P_2}{P_1} \left(\frac{D_2}{D_1}\right)^{\frac{2}{2}-1}$$
(39)

# 6. Flow Deflection Angle and Detonation Wave Angle.

The flow deflection angle 9 is

$$\theta = \tan^{-1} \left( \frac{y}{\chi} \right) \tag{40}$$

The detonation wave angle  $\sigma$  may be found from the geometry of Fig. 8

$$\tan G = \frac{V_{l} - u}{v} = \frac{V_{l}}{v} - \frac{u}{v}$$

Conversion to the starred system gives

$$\tan G = \frac{V_1 a_1^* a_2^*}{v a_1^* a_2^*} - \cot \theta = \frac{M_1 a_1^*}{y a_2^*} - \cot \theta$$

and

$$\sigma = \tan^{-1} \left( \frac{M_1^*}{4 \delta_2^{\prime 2}} - \frac{\chi}{y} \right) \tag{41}$$

# 7. Mach number after a detonation wave.

The Mach number of the flow after the detonation wave is found as a function of  $\,x\,$  and  $\,y\,$ . From Eq. 24

$$M_2^2 = \frac{2 M_2^2}{(\gamma+1)-(\gamma-1)M_2^{*2}}$$

With  $\frac{x^2}{M_2} = x^2 + y^2$  (42)

then  $M_2^2 = \frac{2(\chi^2 + y^2)}{(\chi^2 + y^2) - (\chi^2 + y^2)}$ 

The components of  $M_2$ , namely  $M_{2u}$  and  $M_{2v}$  are

$$M_{2u} = M_2 \cos \theta$$
  
 $M_{2v} = M_2 \sin \theta$ 

## CHAPTER III

## CALCULATIONS AND RESULTS

# 1. Calculations.

Properties concerning the oblique detonation wave, namely  $M_2$ ,  $\theta$ ,  $\sigma$ ,  $\frac{P_2}{P_1}$ ,  $\frac{P_{72}}{P_{71}}$ , and  $\frac{7_2}{7_1}$  were calculated for given values of  $\gamma$ ,  $M_1$ ,  $\gamma$ , and  $\gamma$ , using a Control Data Corporation 1604 digital computer. A program was composed for a specific  $\gamma$ .  $M_1$ ,  $\gamma$ , and  $\gamma$ , were allowed to assume a range of suitable values for three values of  $\gamma$ . These ranges are given in Table I.

TABLE I						
Ranges or Values of Parameters						
Parameter	Range of Values					
8	1.2, 1.3, 1.4					
M <sub>1</sub>	1.5 to 5.0 by increments of 0.50 8.0 to 14.0 by increments of 3.00					
8	1.0 to $\delta_{\rm max}$ by increments of 0.04 or 0.08					
×	$x_{\min}$ to $x_{\max}$ by increments of 0.03 or 0.05					

where

 $\delta_{\rm max}$  is defined by Eq. 27

 $x_{min}$  is the  $Z_1$  value of Fig. 9 and is defined by Eq. 25

 $x_{max}$  is the  $z_2$  value of Fig. 9 and is defined by Eq. 25

For the given set of conditions  $\gamma$ ,  $M_1$ ,  $\delta$ , and  $\kappa$ , the order of calculation and the equations used are given in Table II.

,						
TABLE II						
Order of Calculations						
	Parameter Equation Numb					
1)	M <sub>1</sub>	23				
2)	У	20a				
3)	θ	40				
4)	T	41				
5)	* M <sub>2</sub>	42				
6)	M <sub>2</sub>	24				
7)	$T_2/T_1$	35				
8)	P <sub>2</sub> /P <sub>1</sub>	37				
9)	P <sub>T2</sub> /P <sub>T1</sub>	39				

The Fortran program used for the above calculations appears in Appendix F.

# 2. Results.

shown in Appendices A through D. With one notable exception the graphs are shown with x  $(M_{2u}^*)$  as the abscissa. Selections of the graphs of  $\sigma$  versus x were unintelligible in several cases. When this occurred the flow deflection angle  $\theta$  was used as an abscissa.

#### CHAPTER IV

#### APPLICATIONS

The main application of the data presented in the appendices is the prediction of properties following a stationary oblique detonation wave which has formed on a wedge-like body in a supersonic stream. The actual physical establishment of such waves has been performed only on a small scale in special laboratory apparatus and only the normal detonation wave has been stabilized. Many experiments will be necessary to determine methods by which oblique detonation waves may be stabilized. Estimations of expected temperatures and pressures will be valuable in such experiments. Maximum values of wedge angles and the amount of heat that may be added for a given pre-detonation velocity should also prove useful.

The data in the appendices may also be used to give a first approximation in calculating or comparing the performance of detonation wave ramjet engines. As an example let the engines of Fig. 1 and Fig. 2 be denoted as A and B respectively. Consider these engines flying at an altitude of 50,000 feet at Mach 5. Table III gives the state of the flowing stream at various stations in these engines under the following assumptions:

- 1) Flow conditions at stations 0 and 1 are the same.
- 2) In engine A, a normal detonation wave occurs

# TALLE III

# FLOW CONDITIONS IN A RAMJET ENGINE

Altitude: 50,000 feet Velocity: Mach 5

δ: 1.2 8: 1.4

Configuration	Station	0	1	2	3	4	
Ramjet A	М	5	5	.587	1	2.88	
	p (psia)	1.685	1.685	41.00	29.35	1,685	
	p <sub>T</sub> (psia)	890	890	51.7	51.7	51.7	
0 12 3 4	T (°R)	390	390	3150	2805	1050	
	T <sub>T</sub> (°R)	2340	2340	3370	3370	3370	
	a(ft/sec.)	968.5				1592	
	V(ft/sec.)	4843				4590	
Configuration	Station	0	1	2	CONTRACT OF STREET	4	
Ramjet B	М	5	5	1		2.99	
	p (psia)	1.685	1.685	32.1		1.685	
0 1 4	p <sub>T</sub> (psia)	890	890	61.0		61.0	
	T (OR)	390	390	2805		1210	
	T <sub>T</sub> (O <sub>R</sub> )	2340	2340	3370		3370	
	a(ft/sec)	968.5				1710	
Specific Impulse	V(ft/sec)	4843				5130	
8.90 lb-sec/lb	Area(cross- sectional)	Ао	Ао	Ао		4.19/10	

# FABLE IV

FLOW CONDITIONS IN A RAMJET ENGINE

Altitude: 50,000 feet

Velocity: Mach 5

δ : 1.4 δ : 1.2

Configuration	Station	0	1	2	3	4	
Ramjet A	M	5	3	.72	1	4.03	
	p (psia)	1.685	24.2	182	141.5	1.685	
	p <sub>T</sub> (psia)	890	890	268	268	268	
0 12 3 4	T (°R)	390	835	3100	2805	782	
	T <sub>T</sub> (°R)	2340	2340	3370	3370	3370	
	a(ft/sec.)	968.3				1386	
Specific Impulse	V(ft/sec.)	4843				5600	
23.5 lb-sec/lb	Area(cross- sectional)	Ao	.169Ao	.169Ao	.157Ao	1.69Ao	
Configuration	Station	0	1	2		4	
Ramjet B	M	5	3	1		4.38	
	p (psia)	1.685	24.2	148		1.685	
4	p <sub>T</sub> (psia)	890	890	2795		279.5	
	T (°R)	390	835	2805		780	
	T <sub>T</sub> (OR)	2340	2340	3370		3370	
	a(ft/sec.)	968.5				1380	
Specific Impulse	V(ft/sec.)	4843				6050	
37.5 lb-sec/lb	Area(cross- sectional)	Ao	.169Ao	.169Ao		2.53Ao	

TABLE V FLOW CONDITIONS IN A RAMJET ENGINE

Altitude: 100,000 feet

Velocity: Mach 8

7: 1.4

8: 1.2

Configuration	Station	0	1	2	3	4	
Ramjet A	М	8	3	.750	1	6.60	
	p (psia)	.157	42.0	31.8	243.5	.157	
	p <sub>T</sub> (psia)	1540	1540	462	462	462	
0 12 3 4	T (°R)	419.6	2065	7480	6950	860	
	T <sub>T</sub> (OR)	5790	5790	8340	8340	8340	
	a(ft/sec.)	1005				1440	
Specific Impulse	V(ft/sec.)	8040				9500	
45.4 lb-sec/lb	Area(cross- sectional)	Ao	.0223Ao	.02 <b>2</b> 3Ac	.0209Ac	1.75Ao	
Configuration	Station	0	1	2		4	
Ramjet B	М	8	3	1		6.71	
	p (psia)	.157	42.0	256		.157	
	P <sub>T</sub> (psia)	1540	1540	484		484	
0 1/2 4	T (°R)	419.6	2065	6940		834	
	T <sub>T</sub> (OR)	5790	5790	8340	ì	8340	
	a(ft/sec.)	1005				1417	
Specific Impulse	V(ft/sec.)	8040				9500	
45.4 lb-sec/lb	Area(cross- section)	Ao	.0223Ao	.0223Ac		1.99Ao	

- between stations 1 and 2. In engine B, an oblique detonation wave occurs between stations 1 and 2 such that  $M_2\,=\,1.$
- 3) The properties across the detonation wave may be determined from Appendix G (Y = 1.4) for a S of 1.2 or total temperature ratio of 1.44.
  - 4) Engine A is choked at station 3, i.e.,  $M_3 = 1$ .
  - 5) The flow is fully expanded to ambient pressure by the divergent nozzle so that  $p_4 = p_0$ .
  - 6) The mass flow rate remains constant throughout.
  - 7) Except in the detonation wave, the entire cycle is isentropic.

One measure of the performance of a ramjet engine is

the specific impulse, the pounds of thrust per pound of air flow per second. From Table III engine A may be seen to have the flow velocity at exit smaller than that at the inlet,  $V_4 \le V_0$ . This is unacceptable. The exit velocity of engine B is greater than the inlet velocity and the specific impulse is 8.90. This is low compared to specific impulse estimations for a conventional type ramjet  $^6$ . Since the exit pressure is fixed at ambient pressure, the total pressure at station 4 is the determining factor for the Mach number at exit. From Appendix G it may be seen that the total pressure losses across detonation waves are smaller at lower Mach numbers. The reason for the converging inlet duct of the ramjet shown in Fig. 3 is now evident.

Let the inlet ducts of engines A and B be such that the stream is isentropically compressed from free stream Mach number M<sub>O</sub> of 5 to a pre-detonation Mach number M<sub>1</sub> of 3. Other assumptions remain the same as in the examples of Table III. Table IV gives conditions at stations in engines A and B. The specific impulse of A is 23.5 and B is 37.5. As expected, A has a smaller specific impulse due to greater losses in the stronger (normal) detonation wave.

A final example is shown in Table V for ramjet A and B at 100,000 feet and Mach 8. A specific impulse higher than any of the previous cases is shown. The high temperatures associated with hypersonic speeds may be noted. The pre-detonation temperature of 2065° R may be sufficient to allow the detonation to occur spontaneously.

The cross-sectional areas were calculated for the engines in Tables III, IV, and V. The range of values of exit to inlet areas is from 1.69 to 4.19. Such sizes seem possible for a ramjet configuration. The inlet duct ratios  $A_{\rm O}/A_{\rm I}$  are high, becoming almost 50 for the Mach 8 example. The efficiency or recovery factor of such an inlet duct will not be large.

More accurate values of performance parameters may be obtained by including representative efficiencies for the various stages, and by adjusting mass flow rate and appropriately. Performance parameters as specific

fuel consumption, mass flow rate, specific impulse and thermal efficiency can be estimated and optimized for various altitudes, flight Mach number, pre-detonation Mach number and amount of heat addition.

Although the values for the examples of Tables III,

IV and V are not exact, they provide rough estimations of
what can be expected, and may suggest methods for design
improvement or for increasing the performance.

## CHAPTER V

#### CONCLUSIONS

At the present time the interest in stationary detonation waves is primarily academic because of the lack of experimental data. Theoretically the use of detonation waves is a feasible method for supersonic combustion.

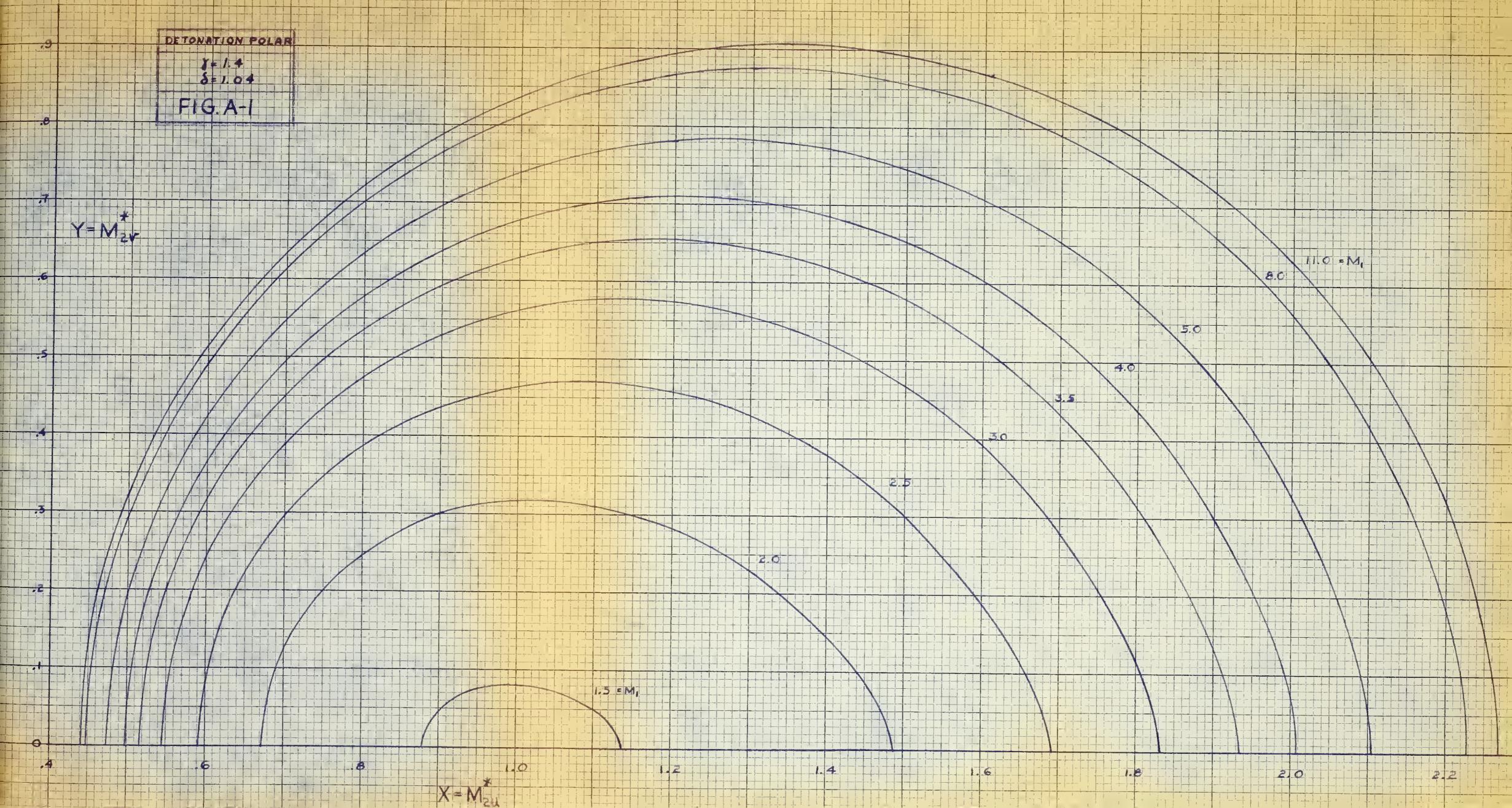
Supersonic burning has been achieved without resort to detonation and the losses associated with detonation. But expensive, not readily available, exotic fuels such as aluminum borohydride are necessary whereas detonation wave combustion may be accomplished with common hydrocarbon fuels. The temperatures encountered in supersonic combustion are beyond the structural capabilities of any materials now in use. While external combustion or detonation may provide a means to lessen the effects of high temperature, external combustion is also in the theoretical category.

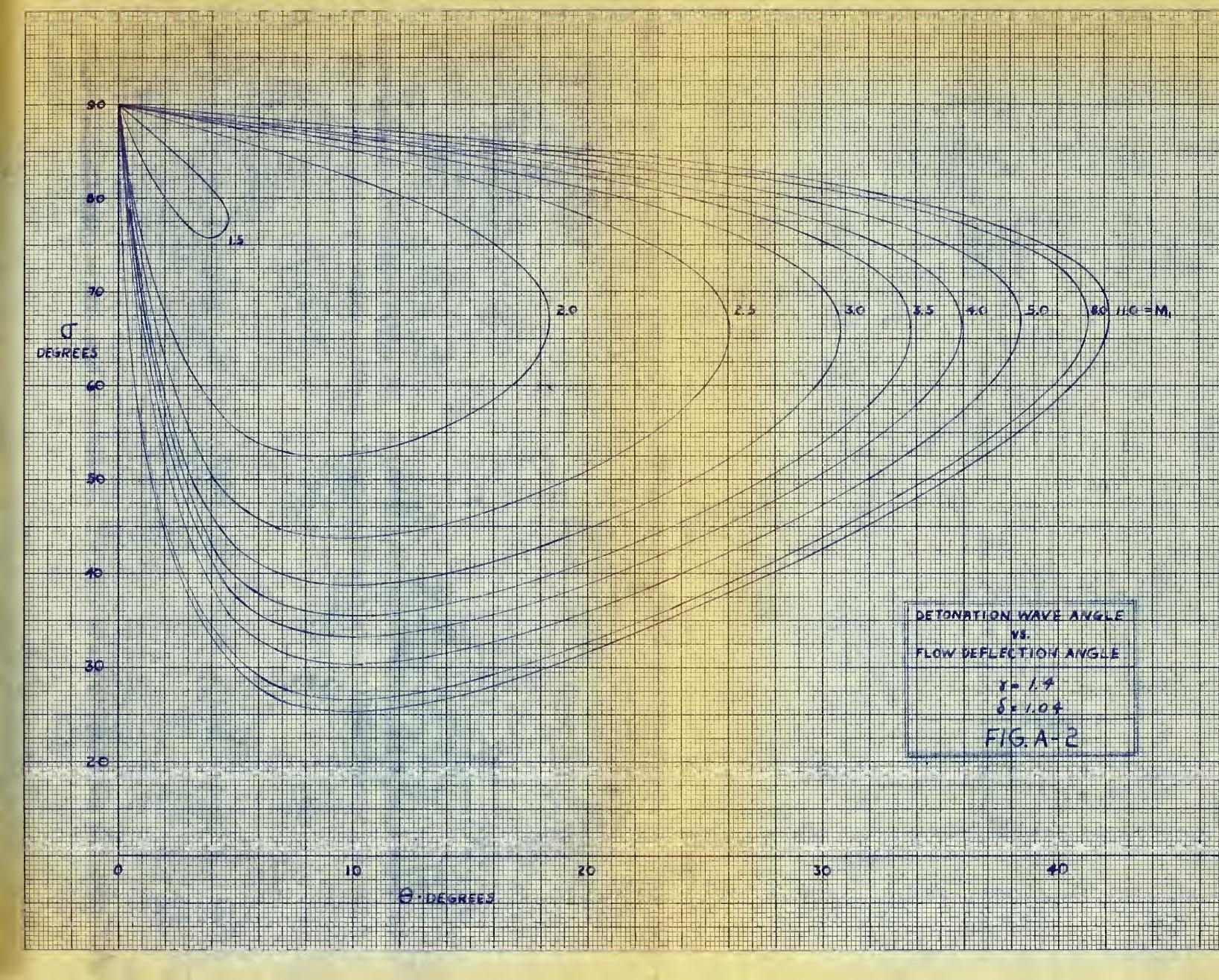
It may be concluded that a detonation wave process in a propulsive unit is a possibility, but it is still a method of the future and will depend on experimental progress in stabilization of detonation waves and technological advances in structural materials.

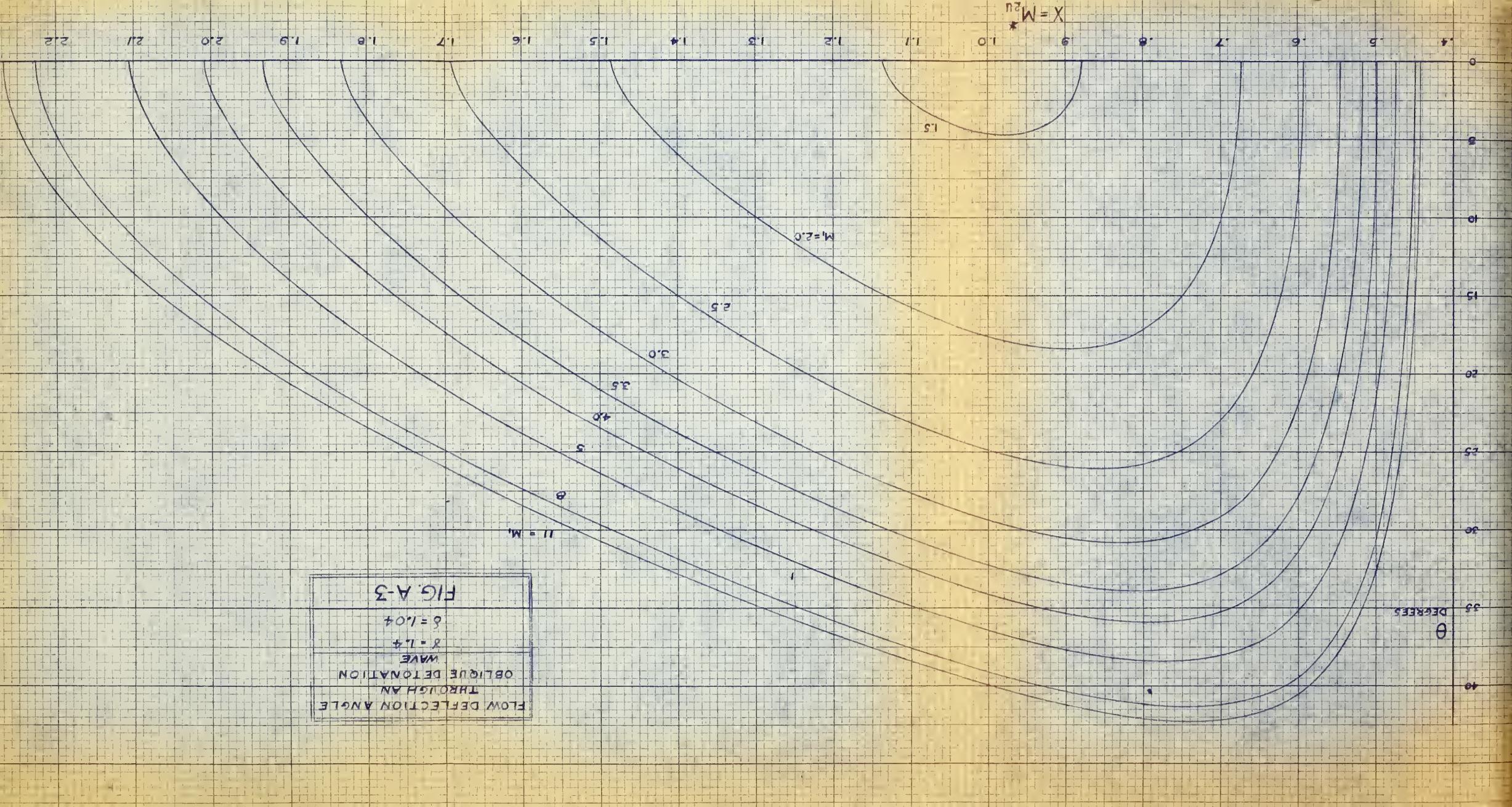
#### REFERENCES

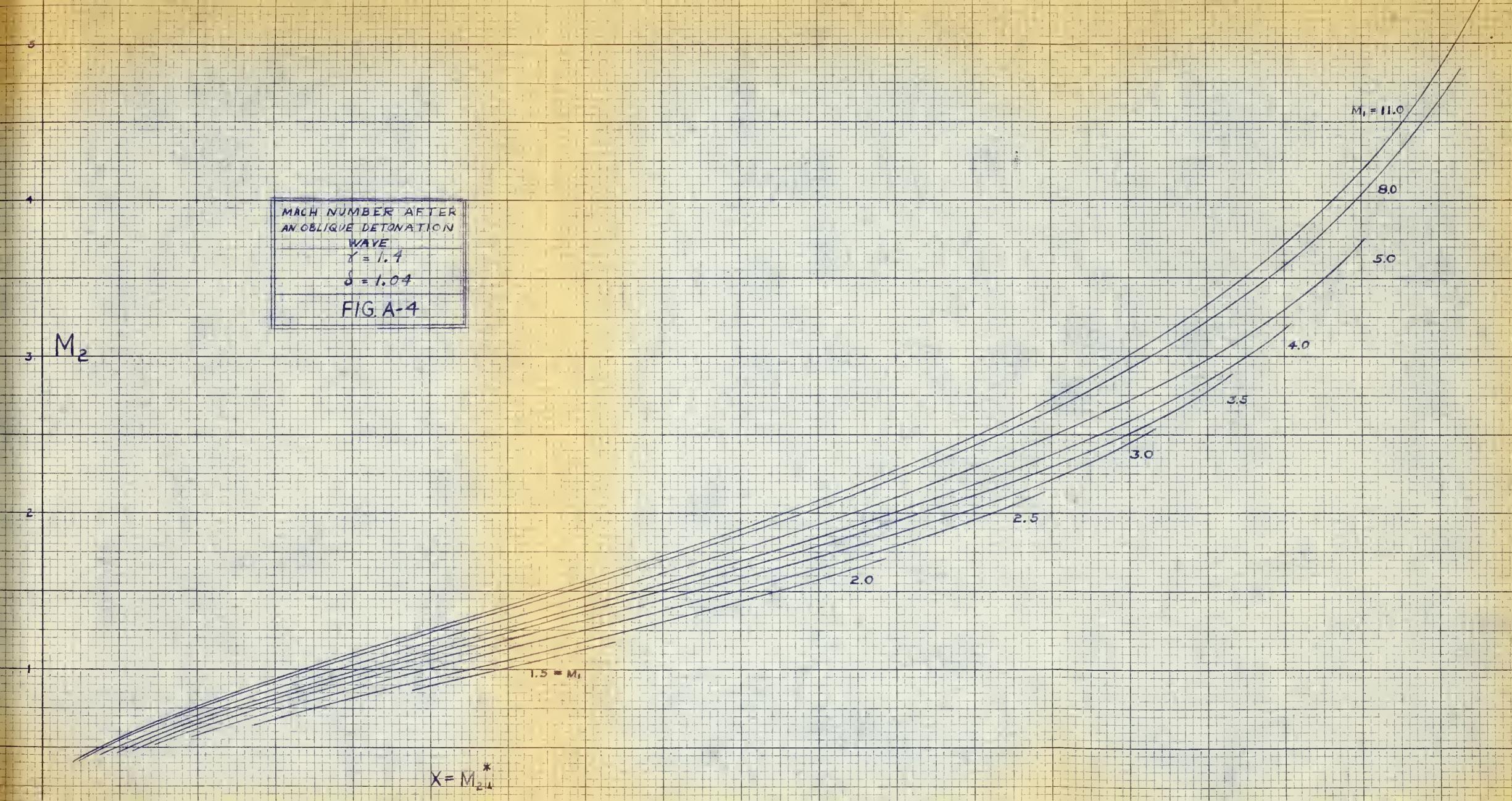
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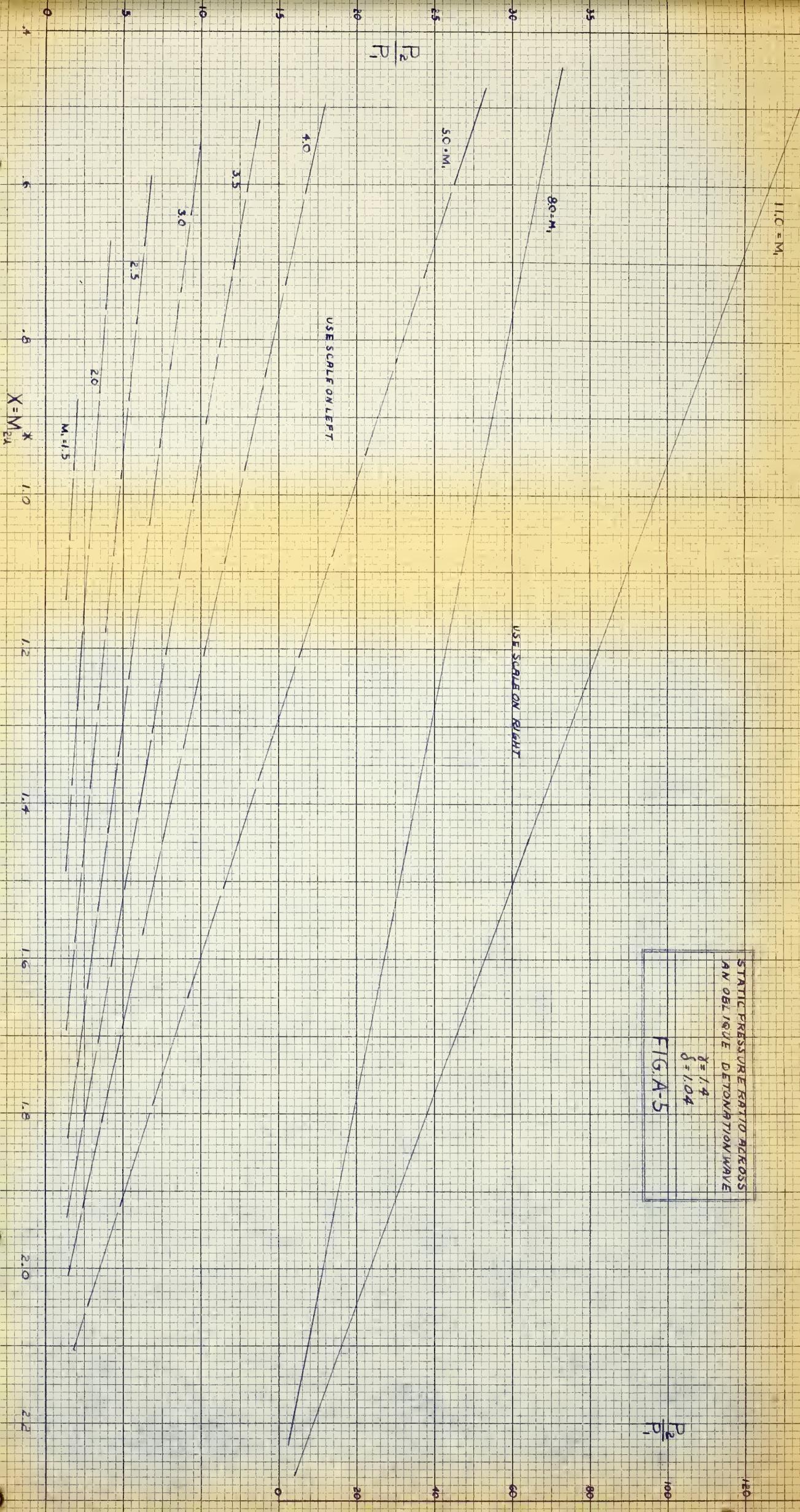
APPENDIX A

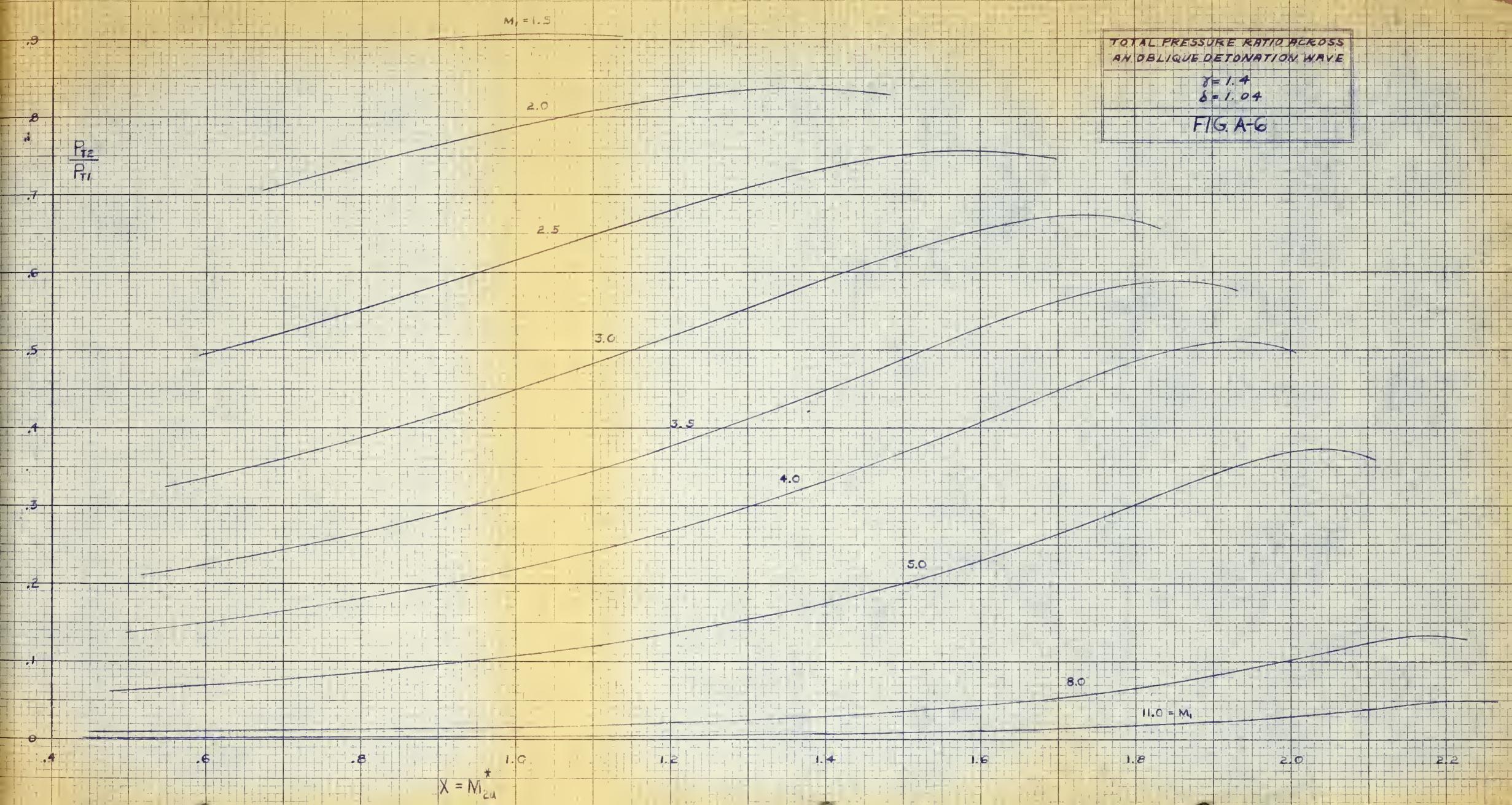


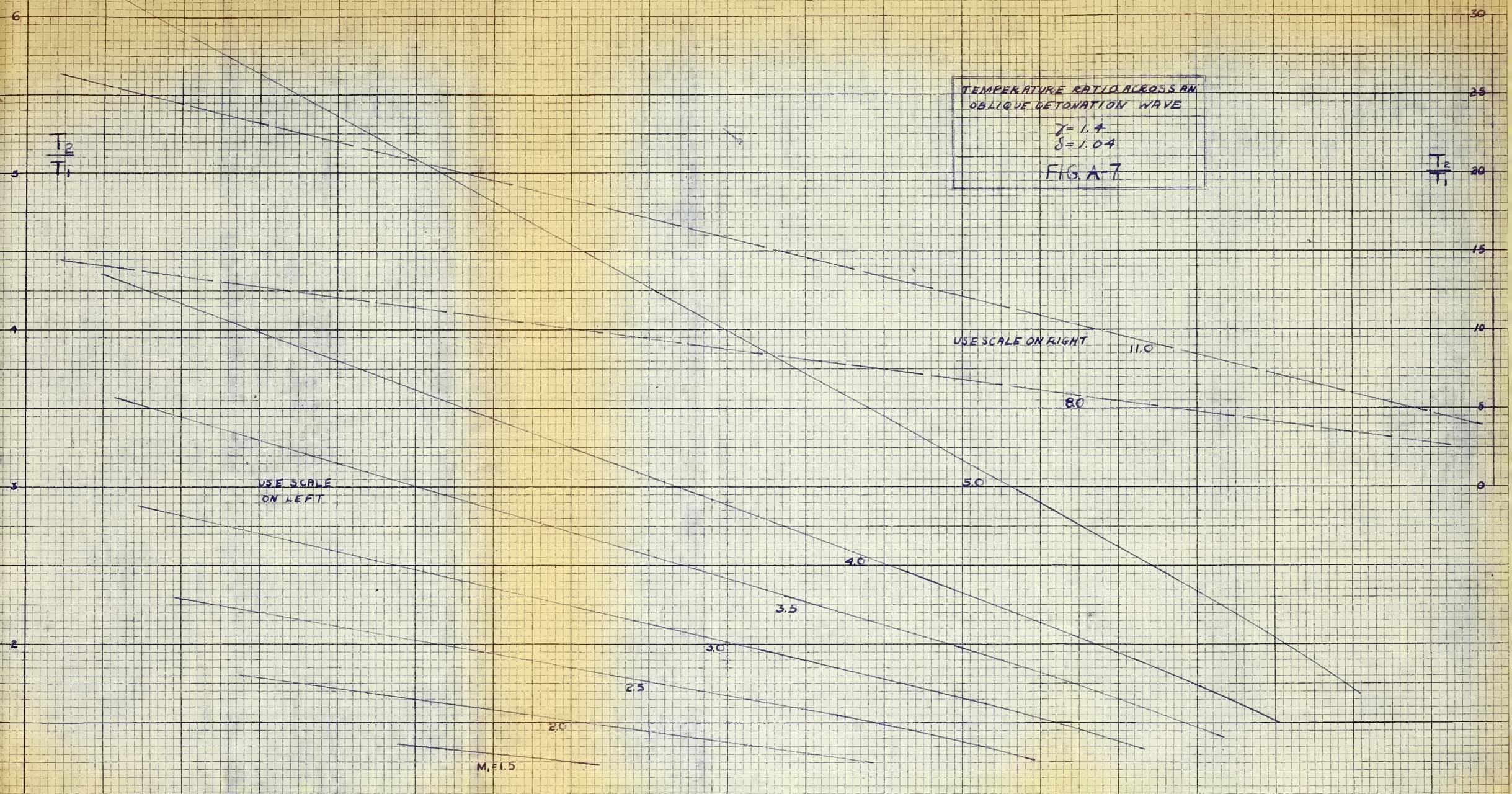




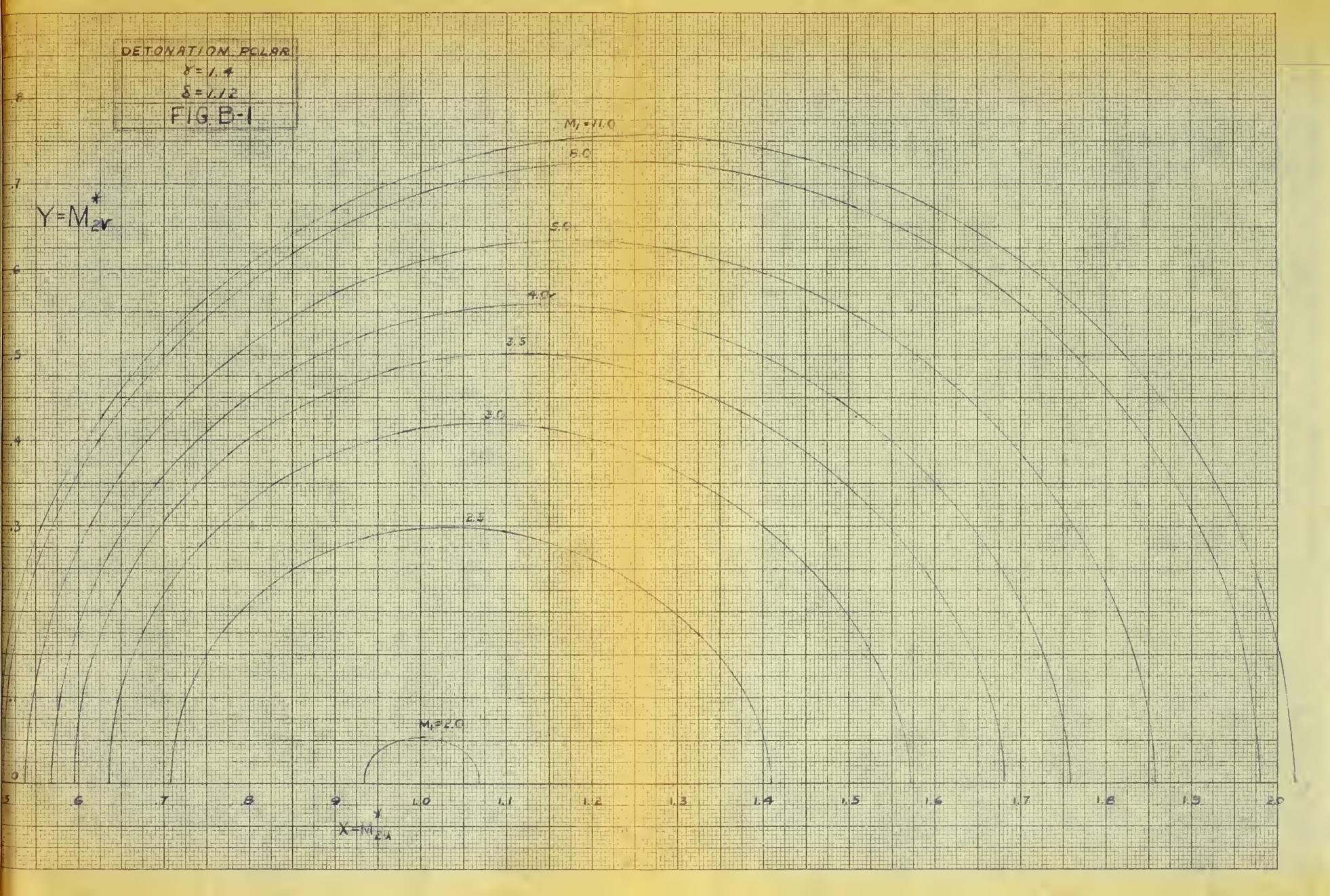


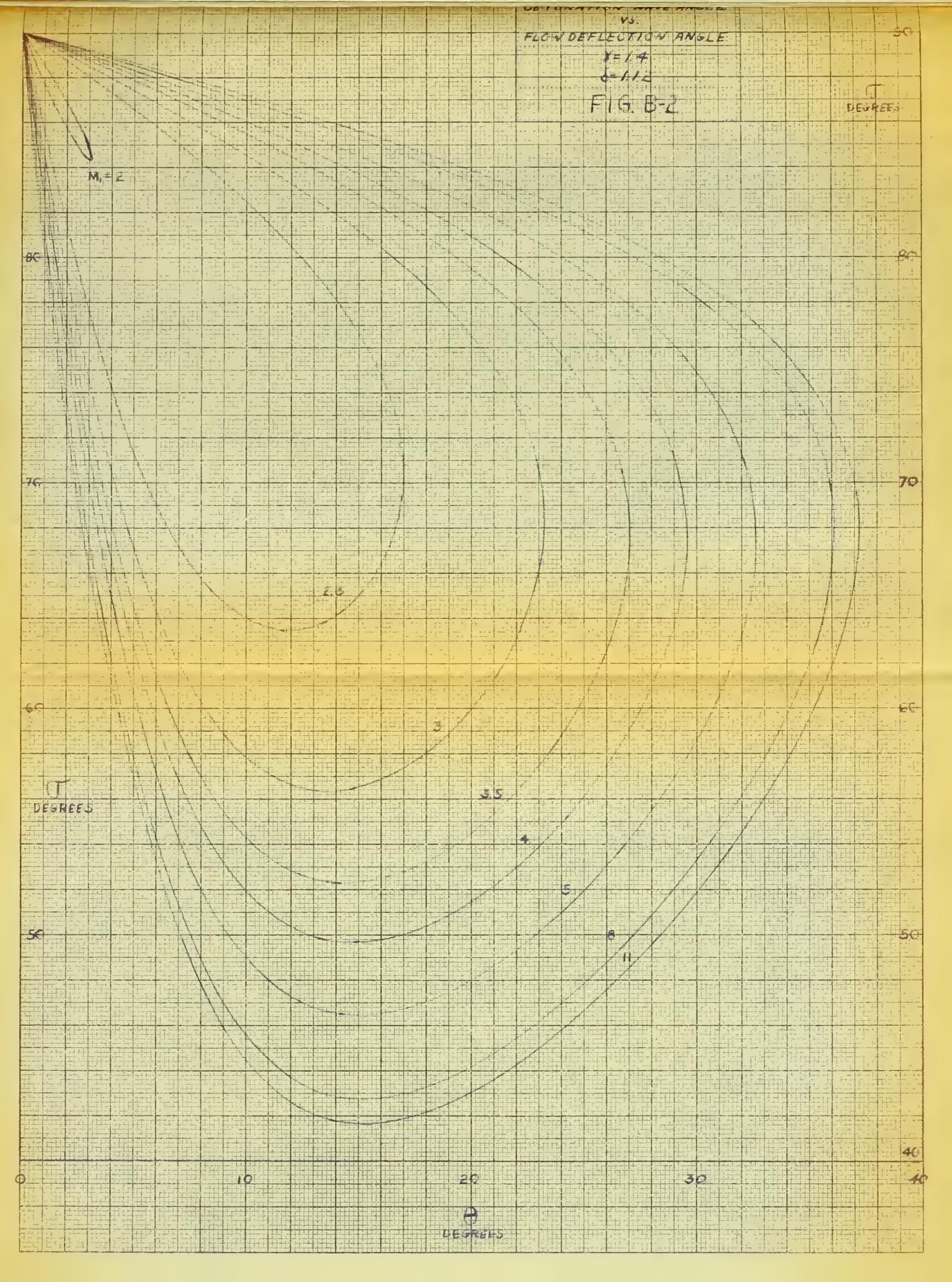


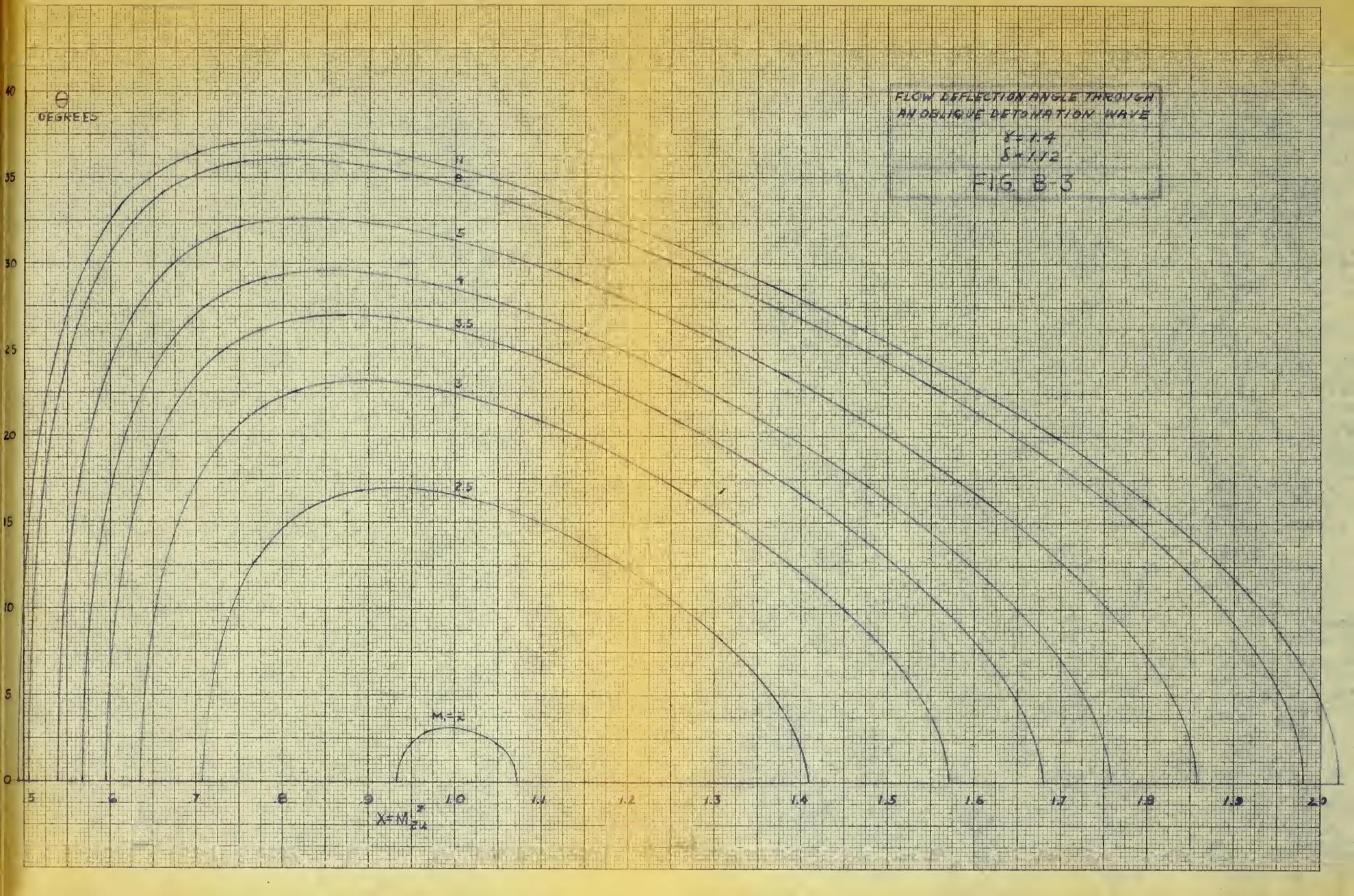


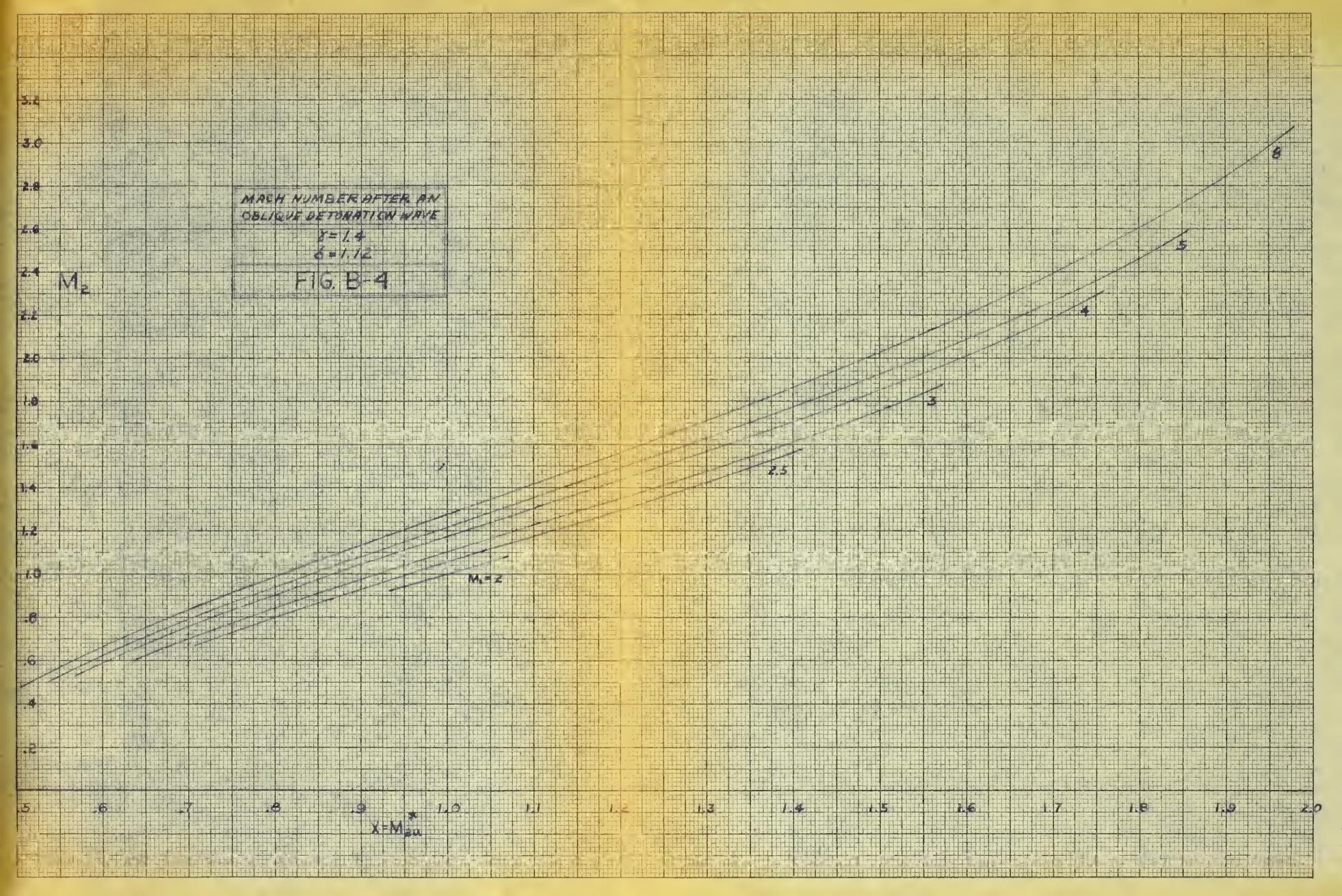


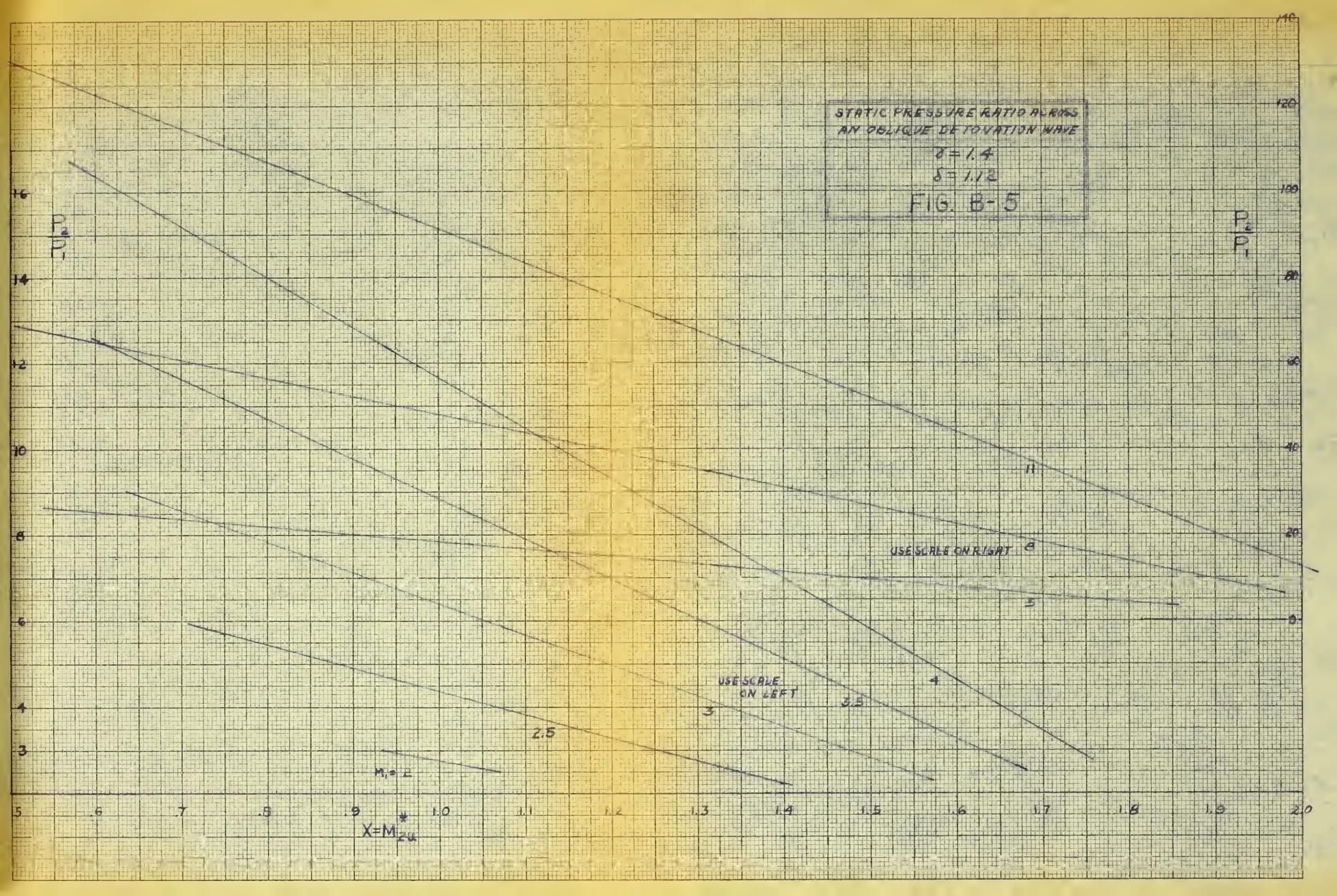
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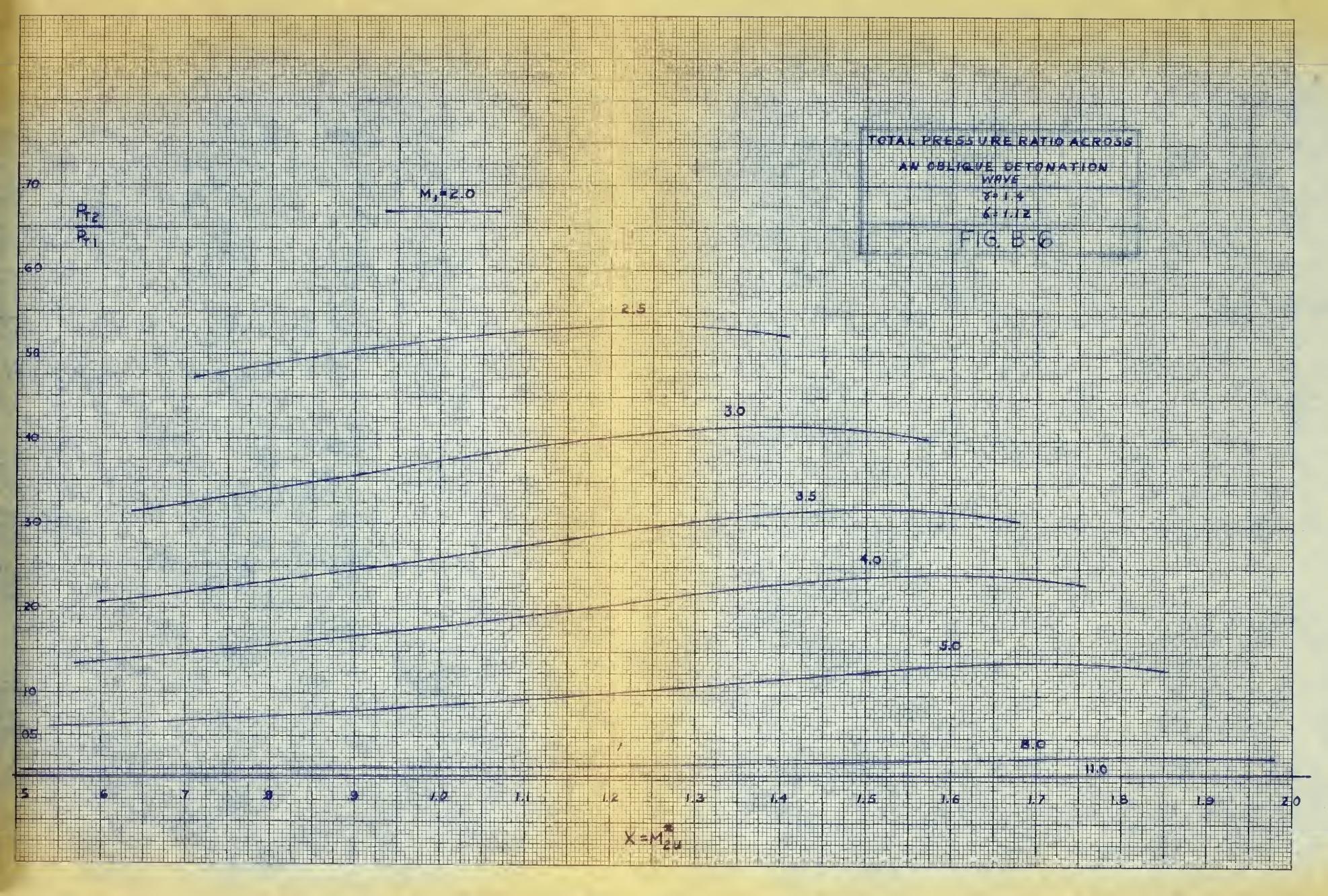


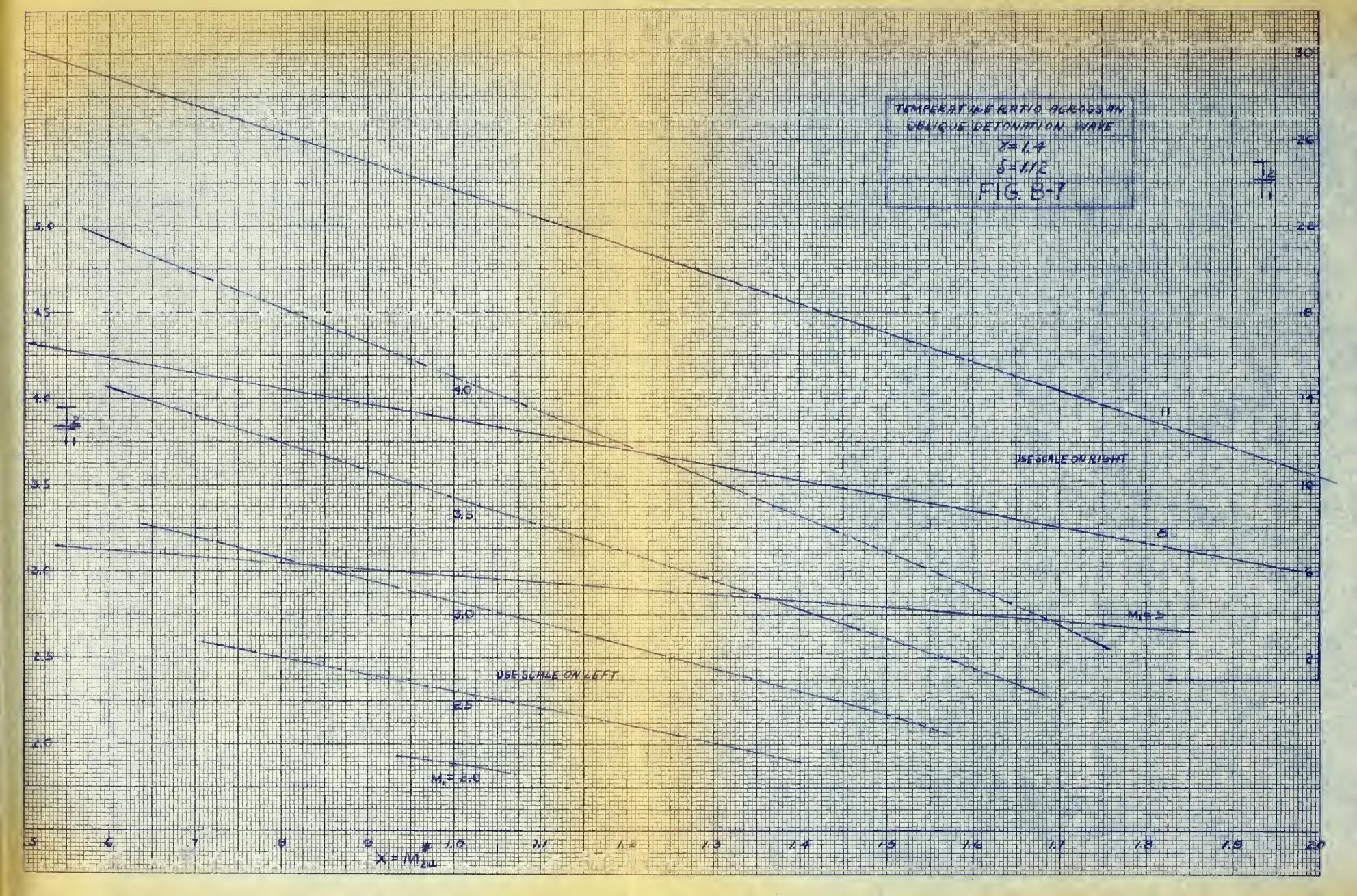




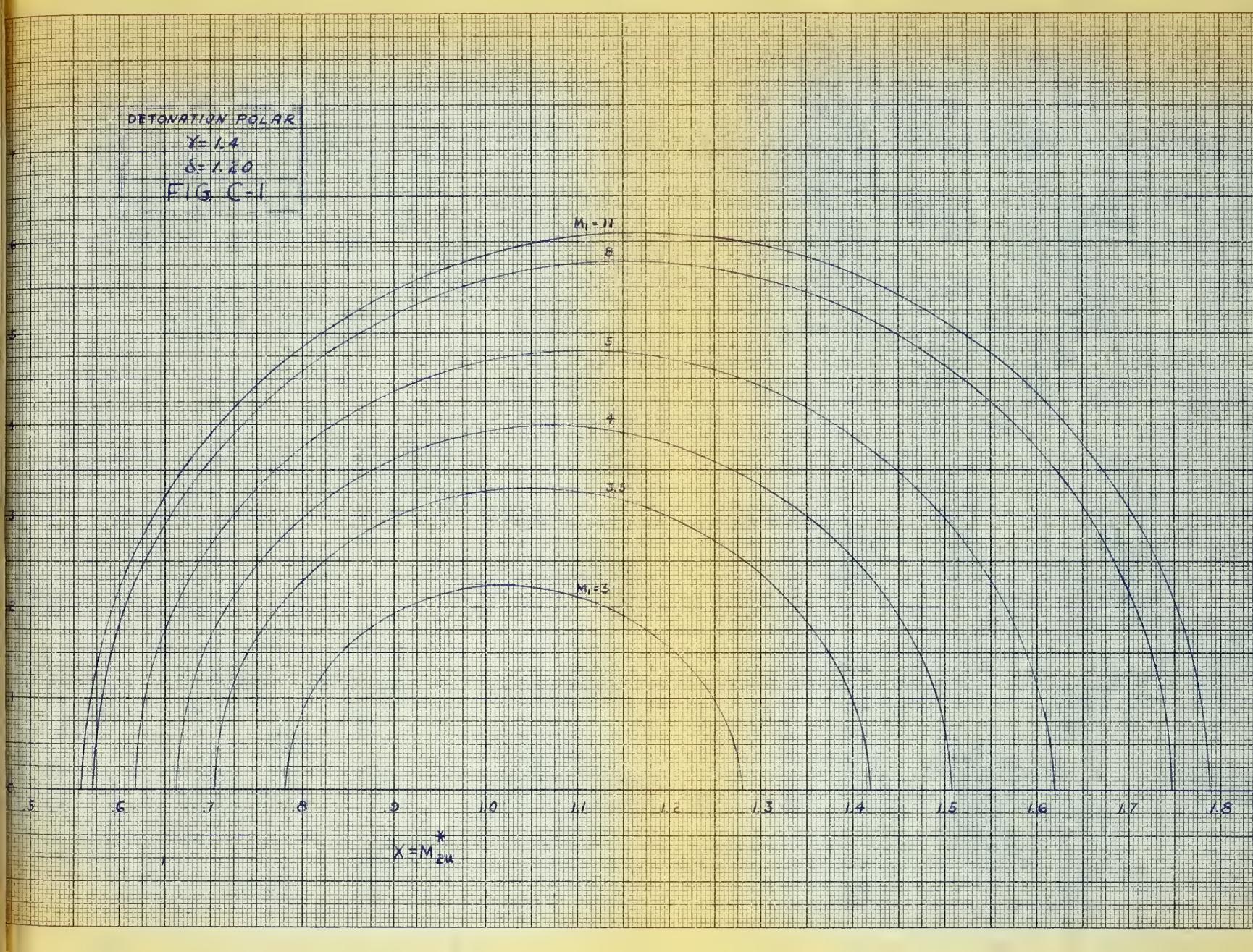


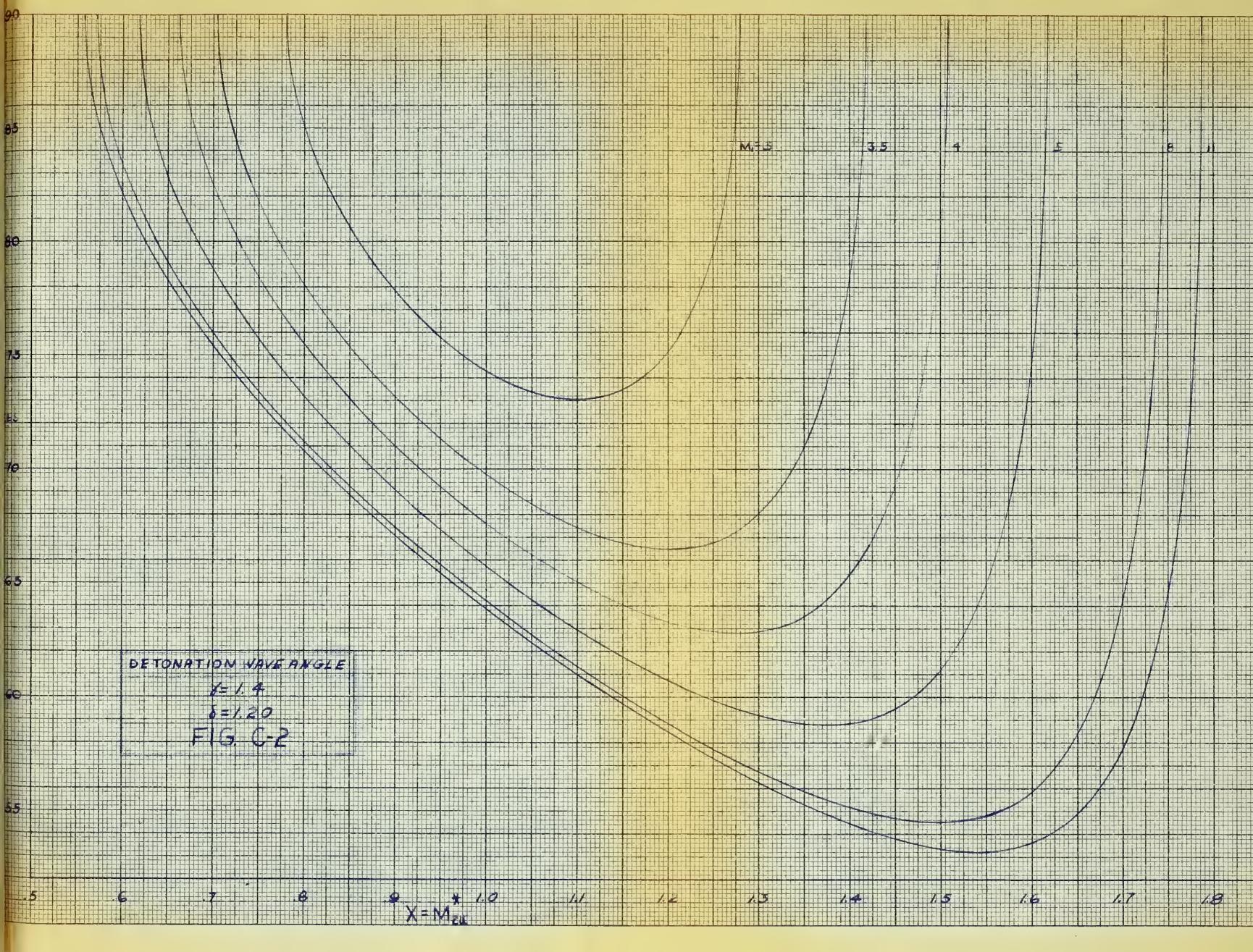


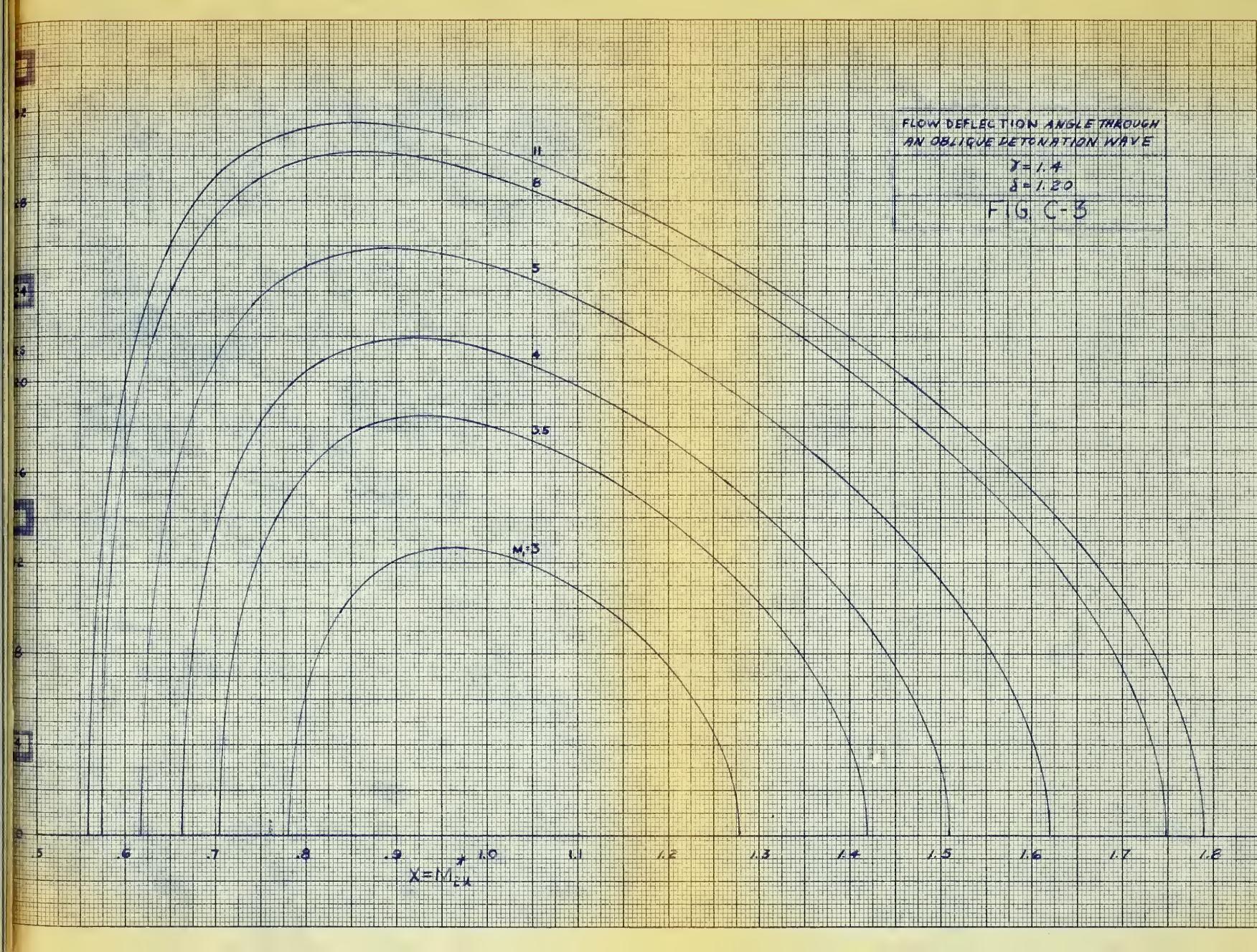


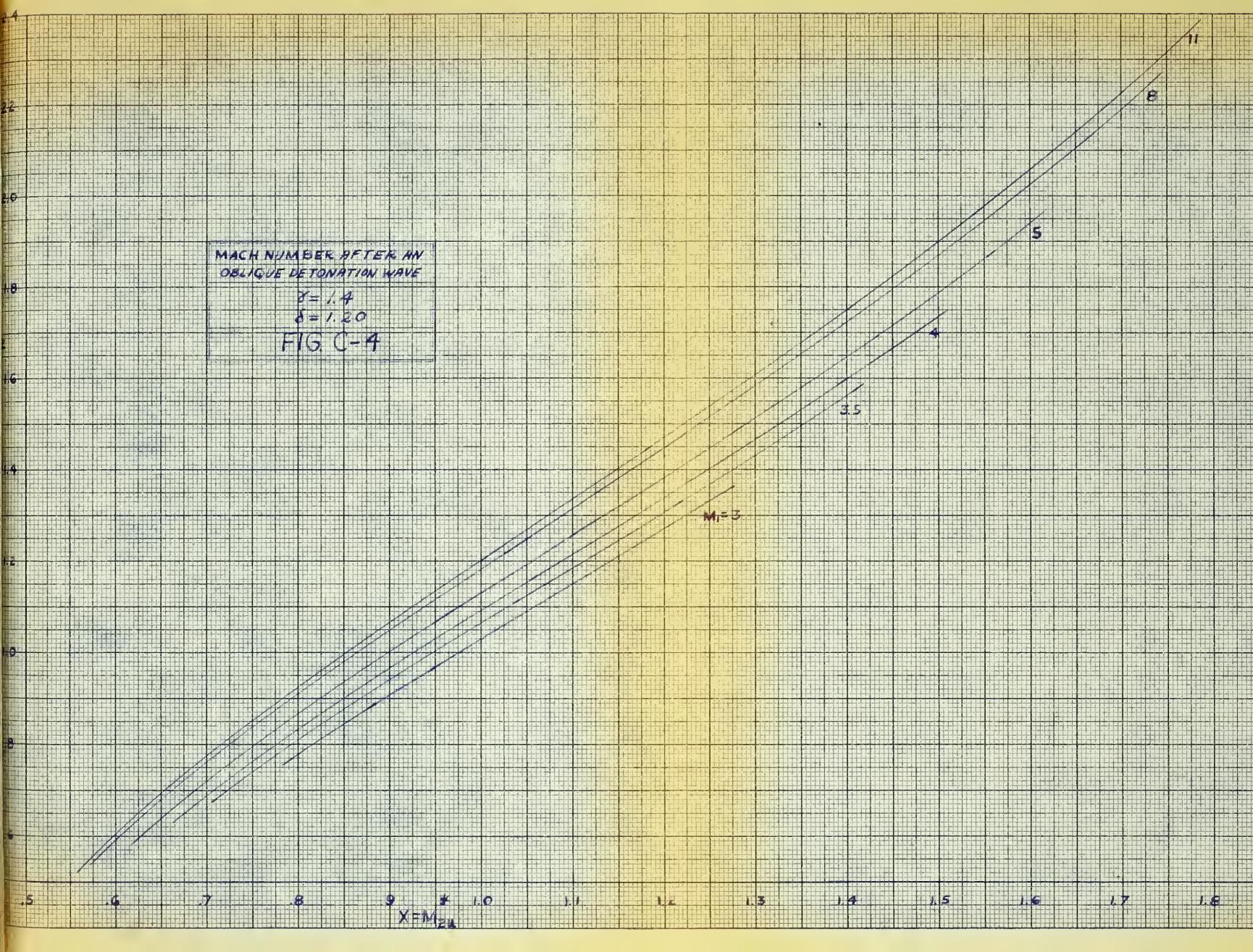


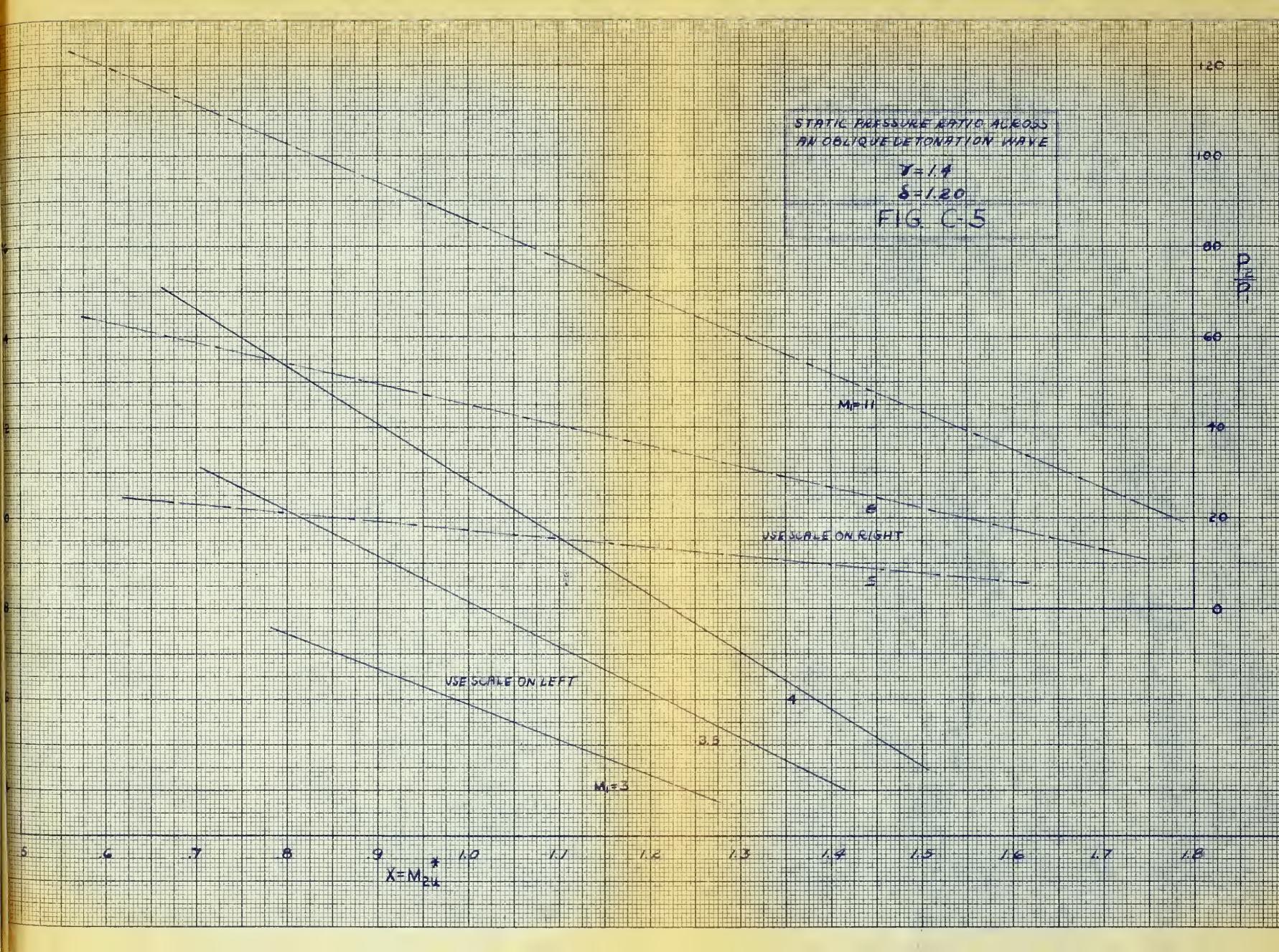
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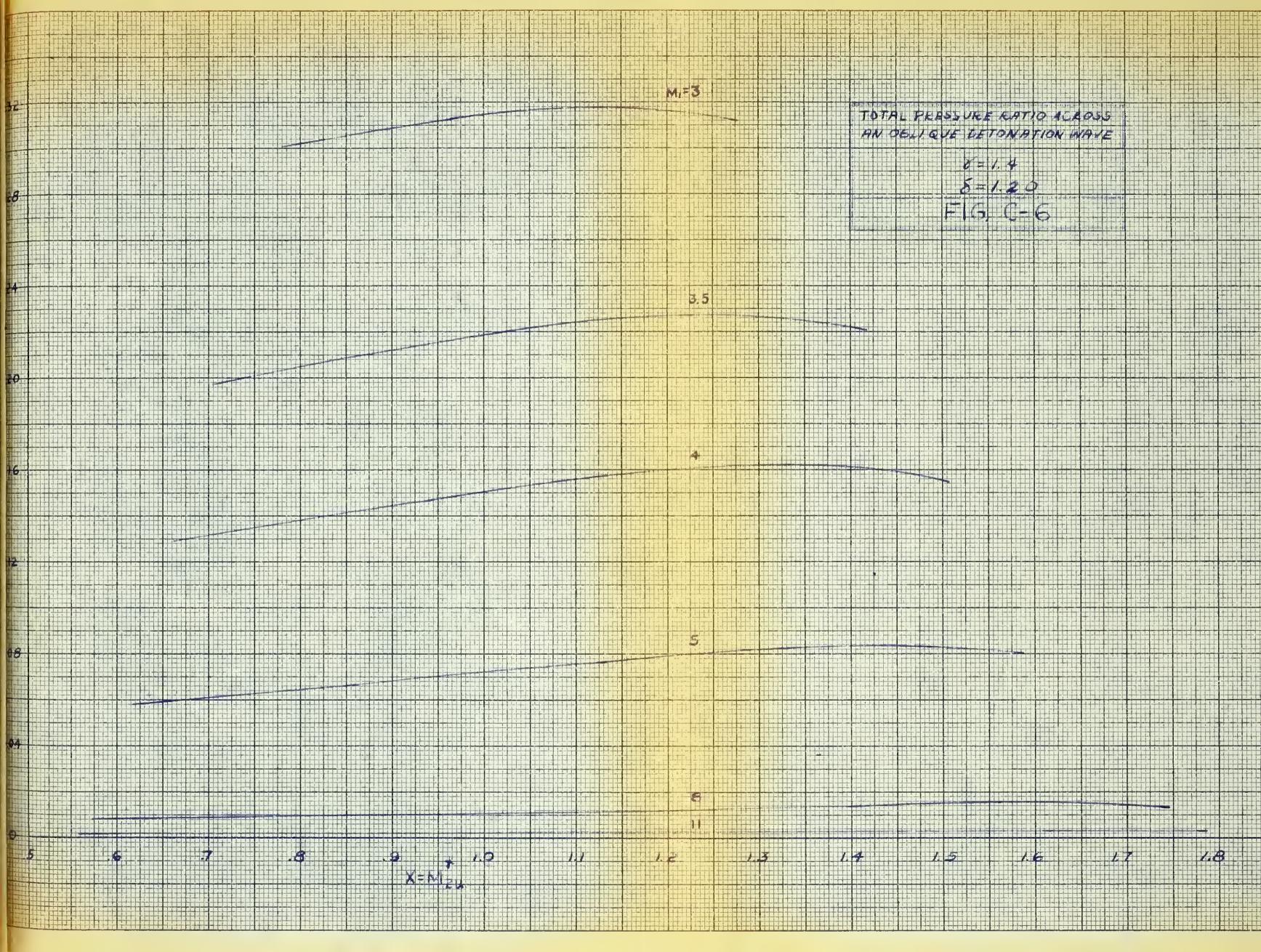


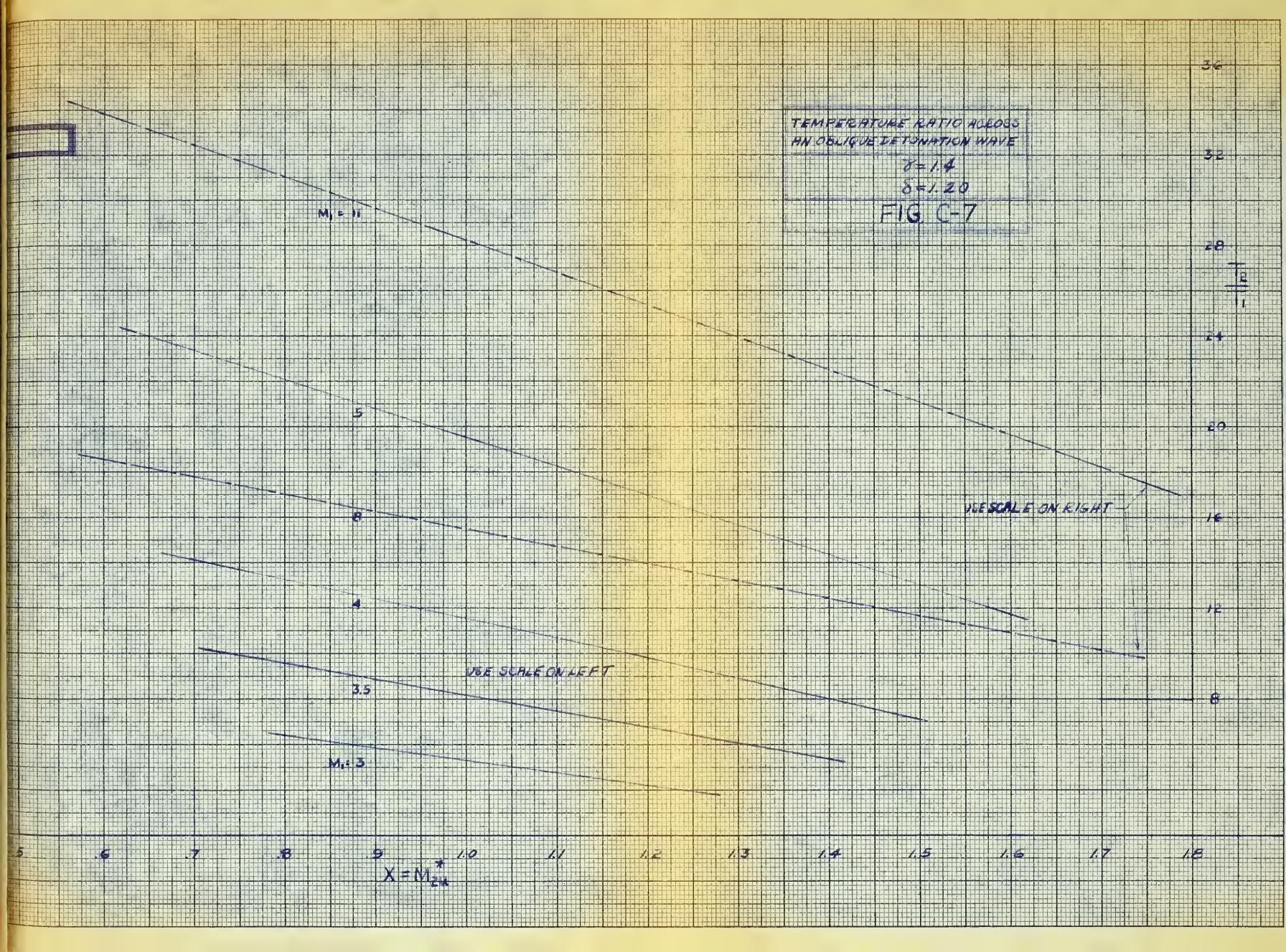




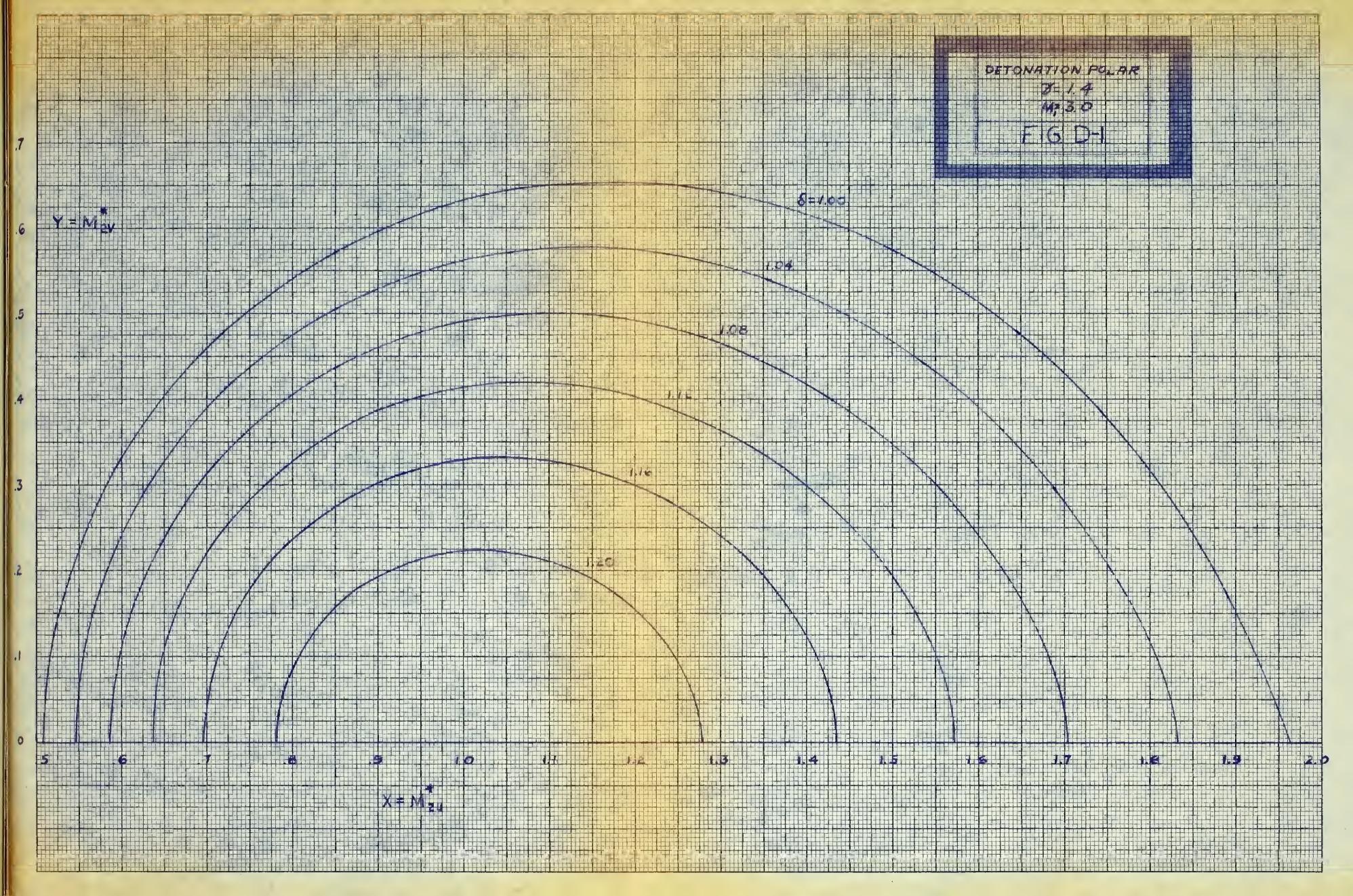


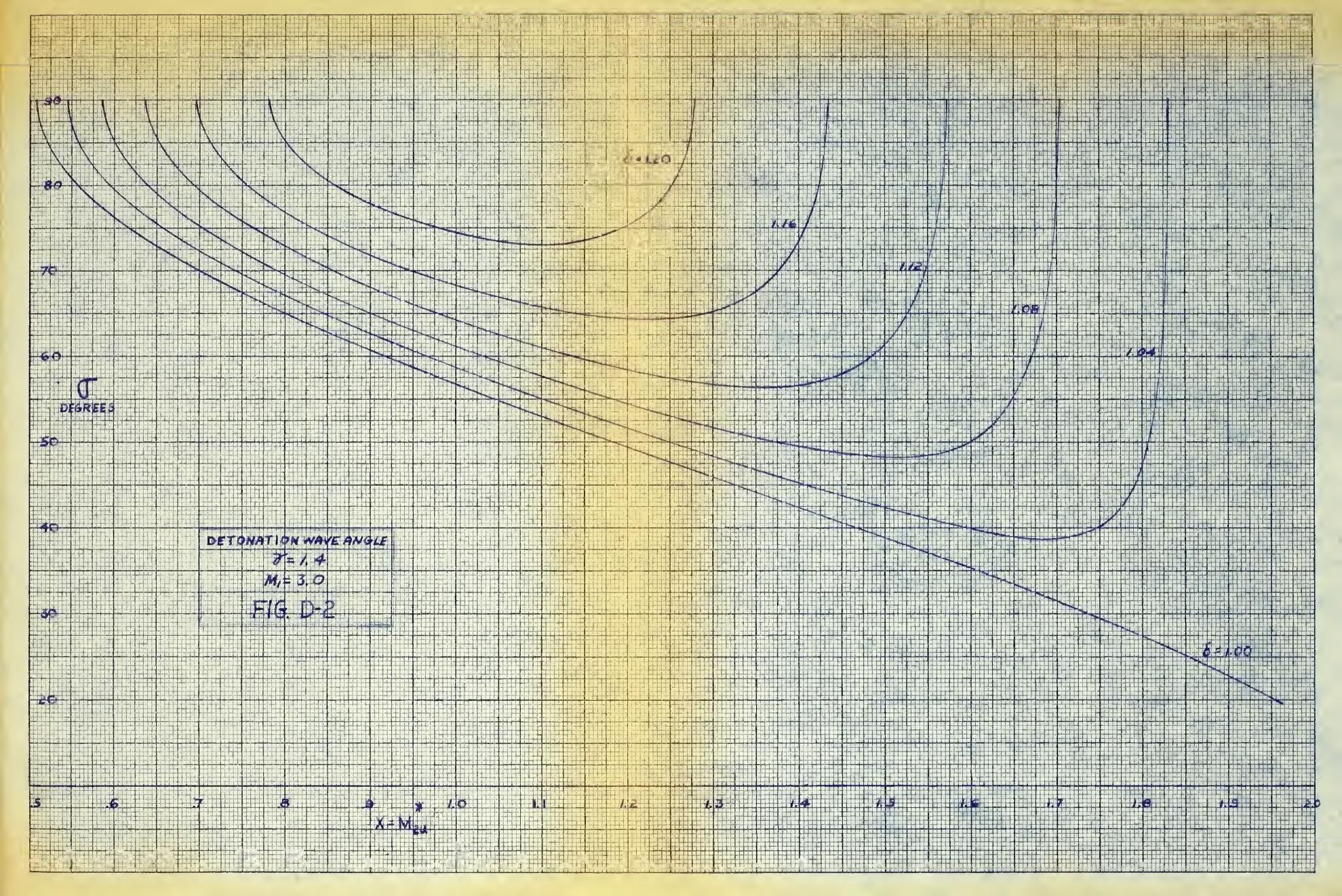


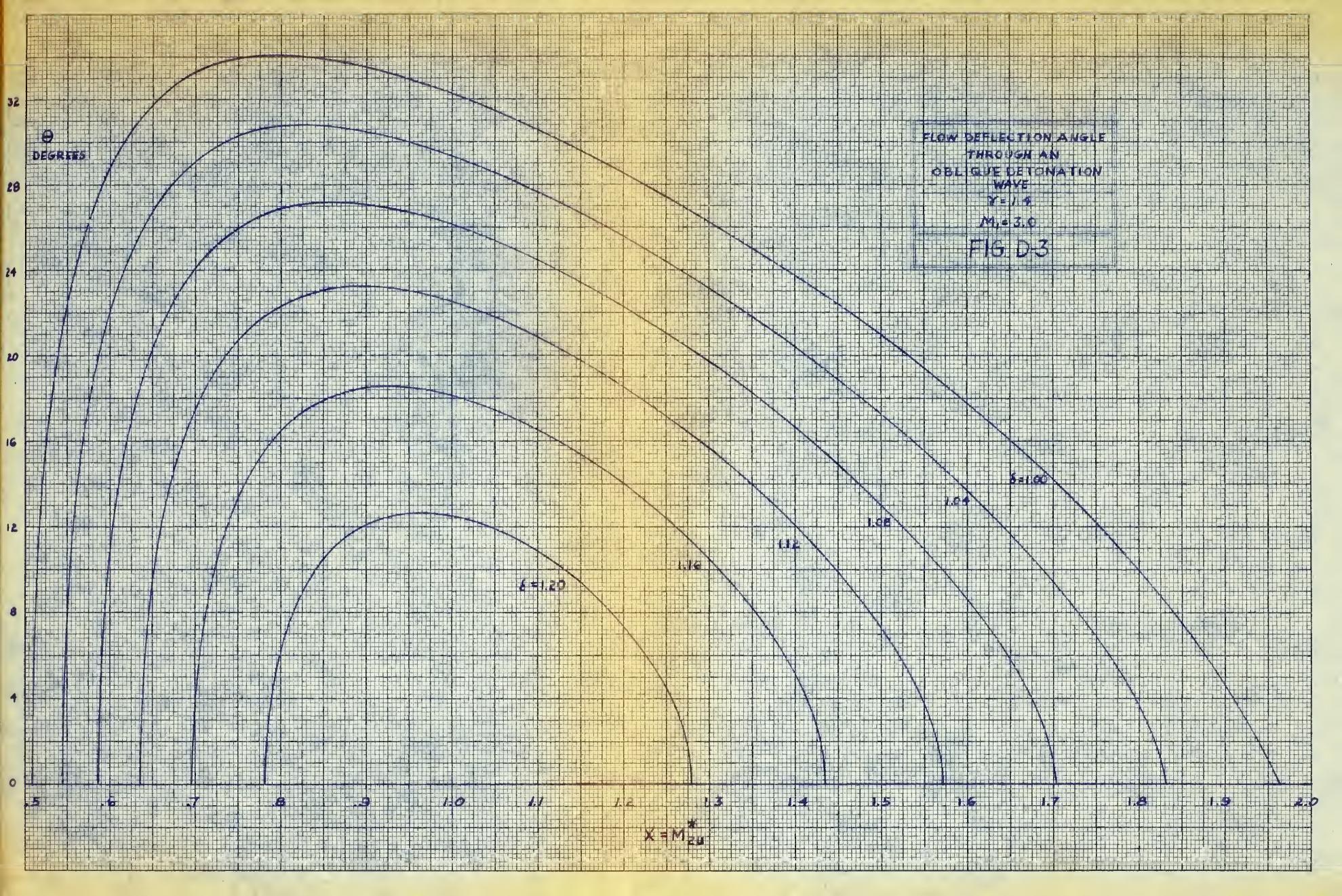


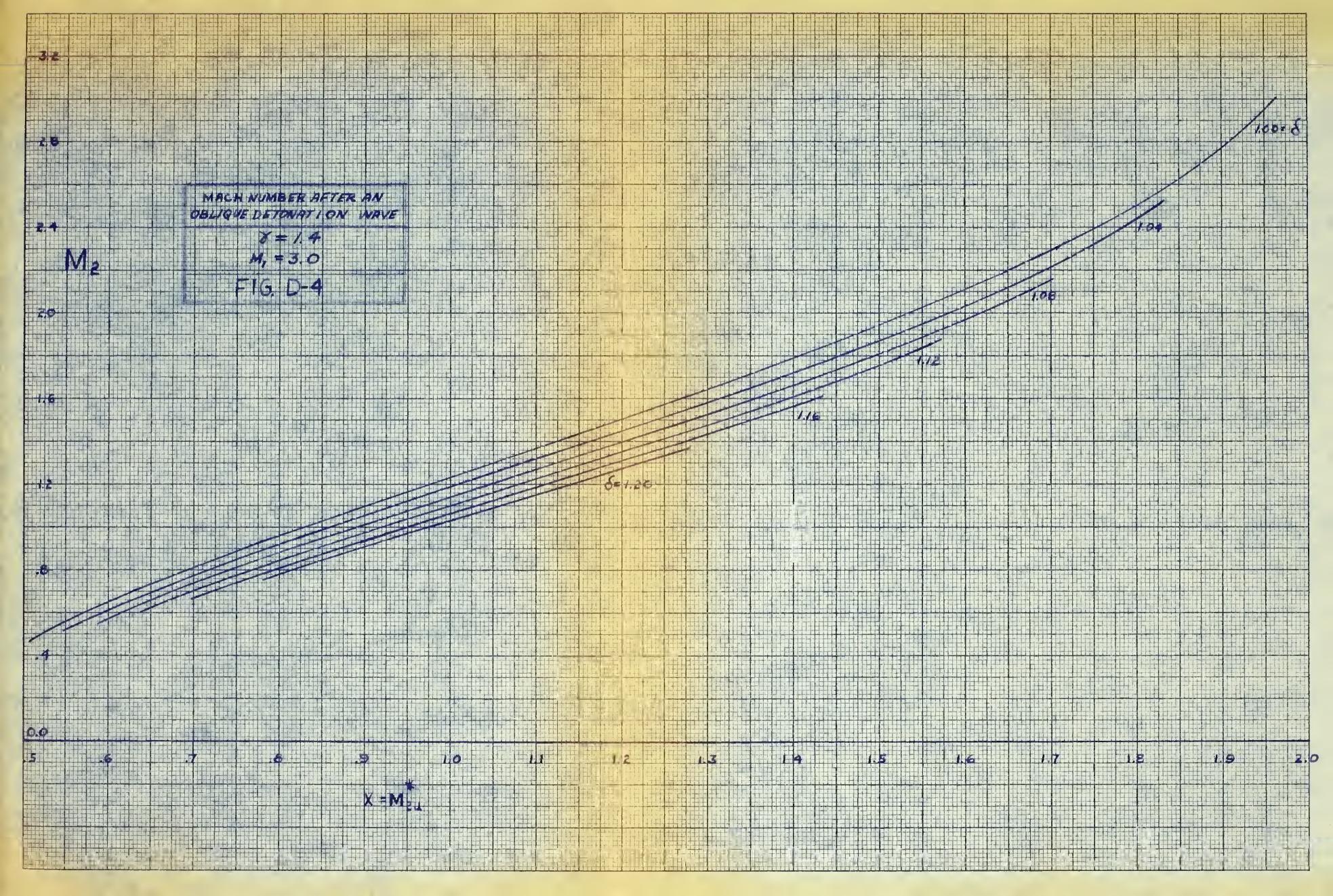


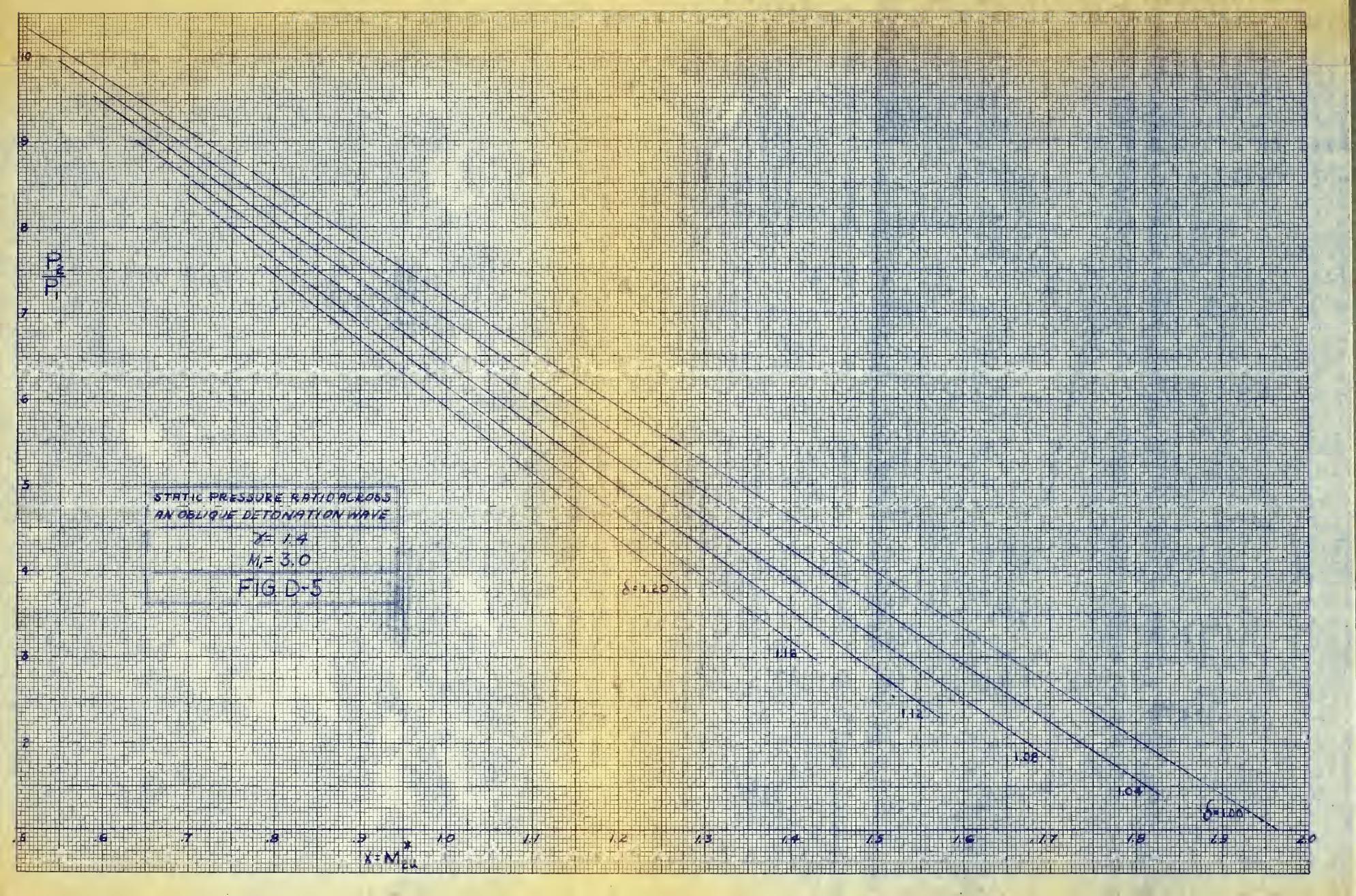
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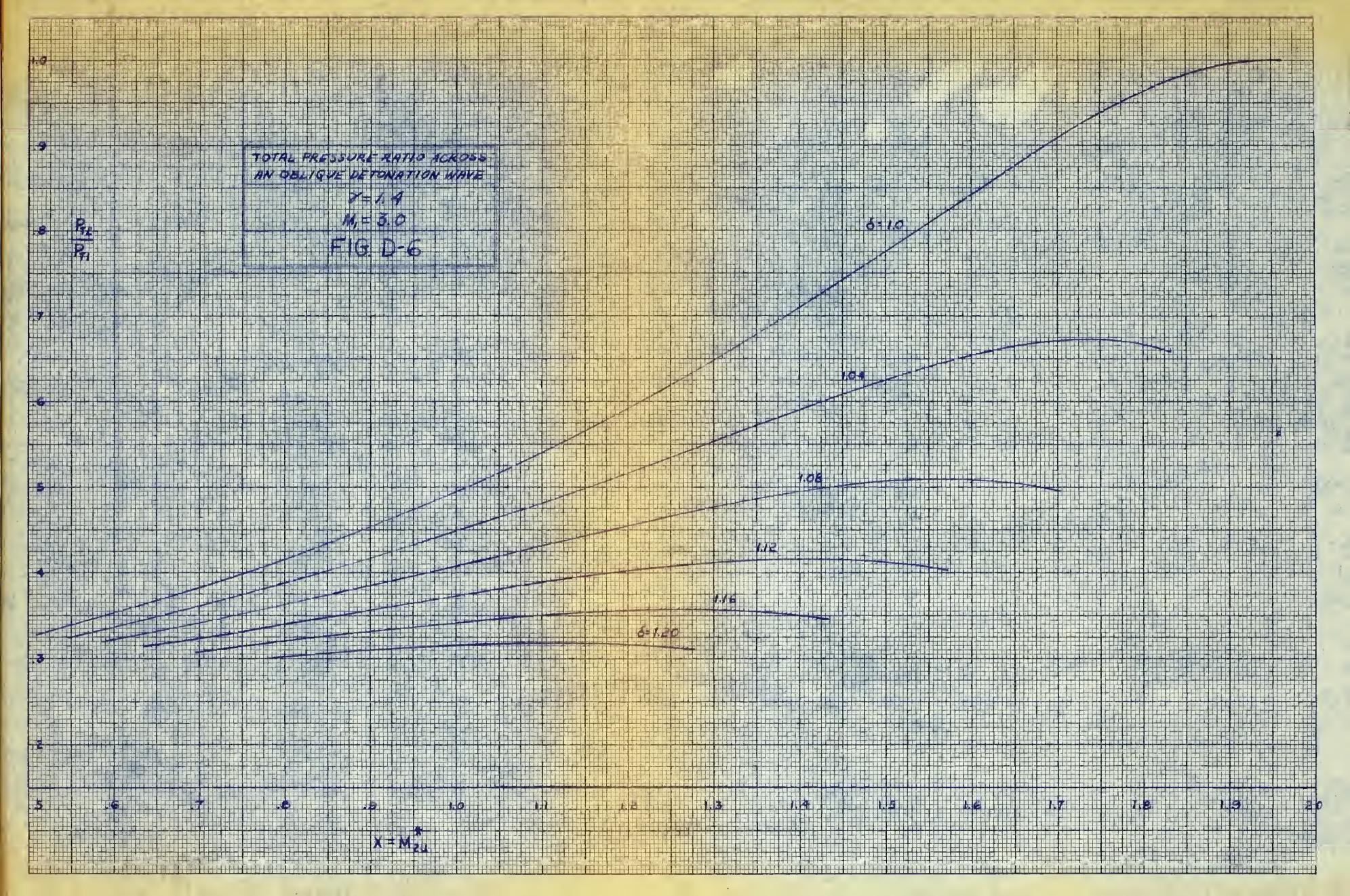


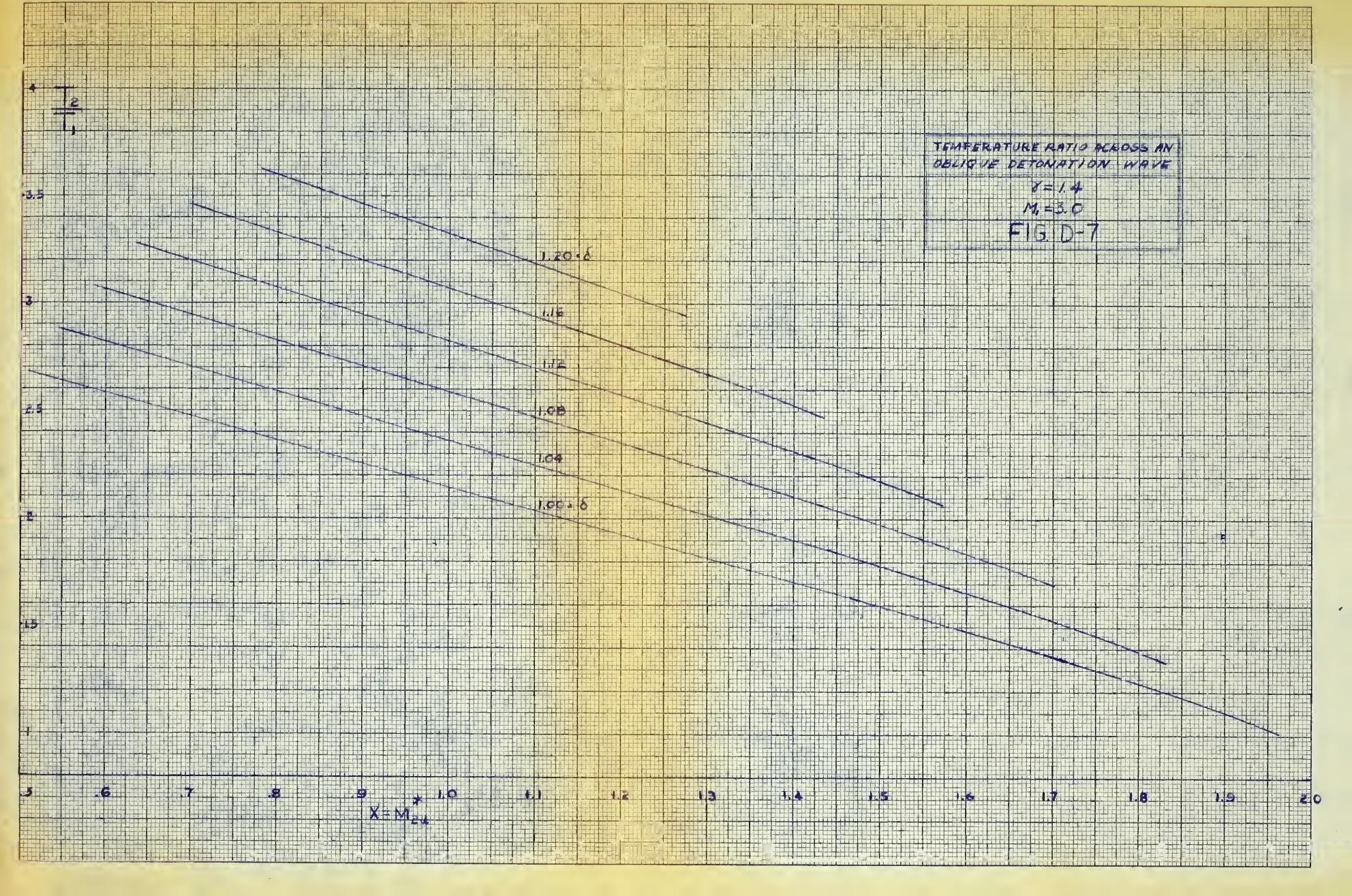




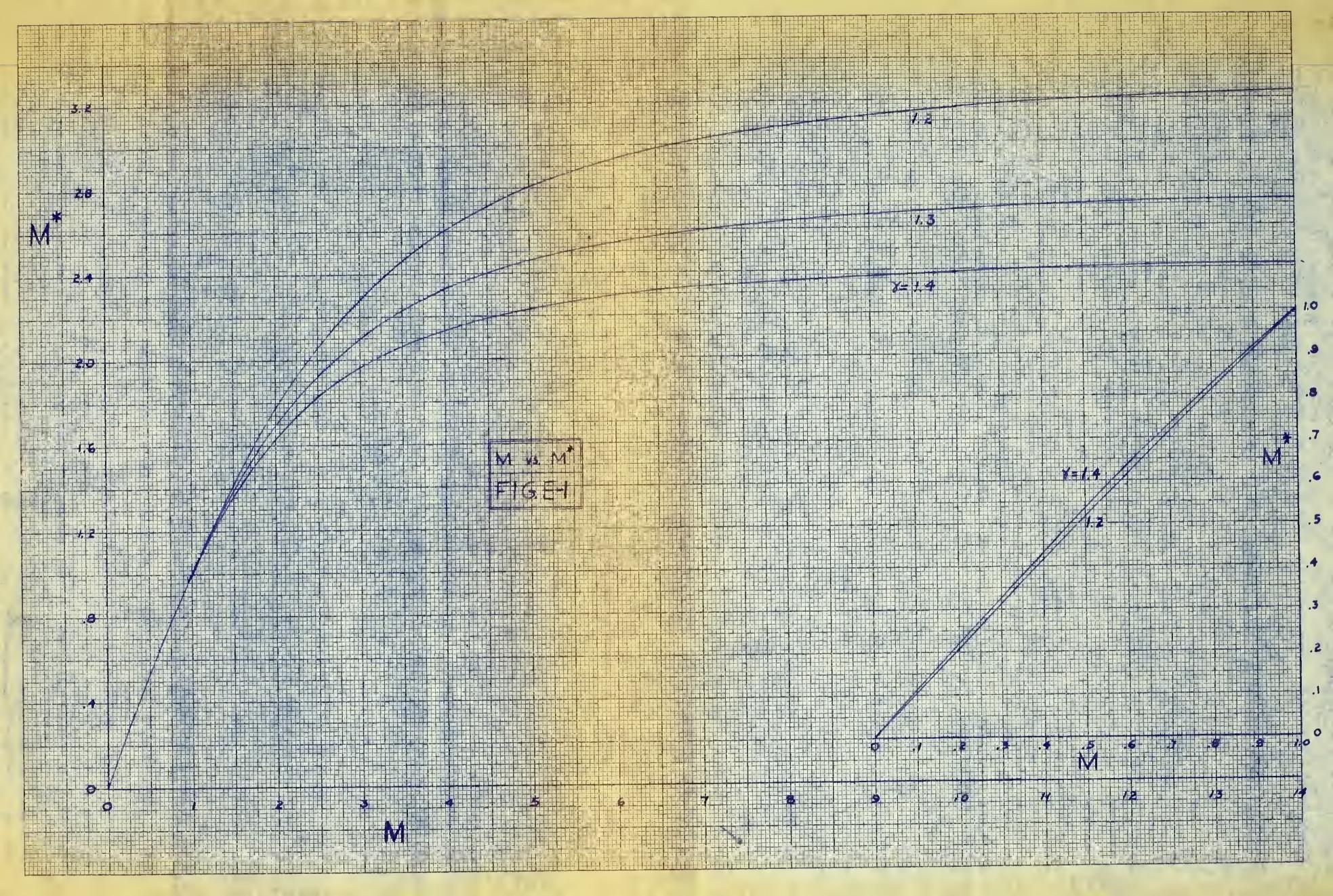


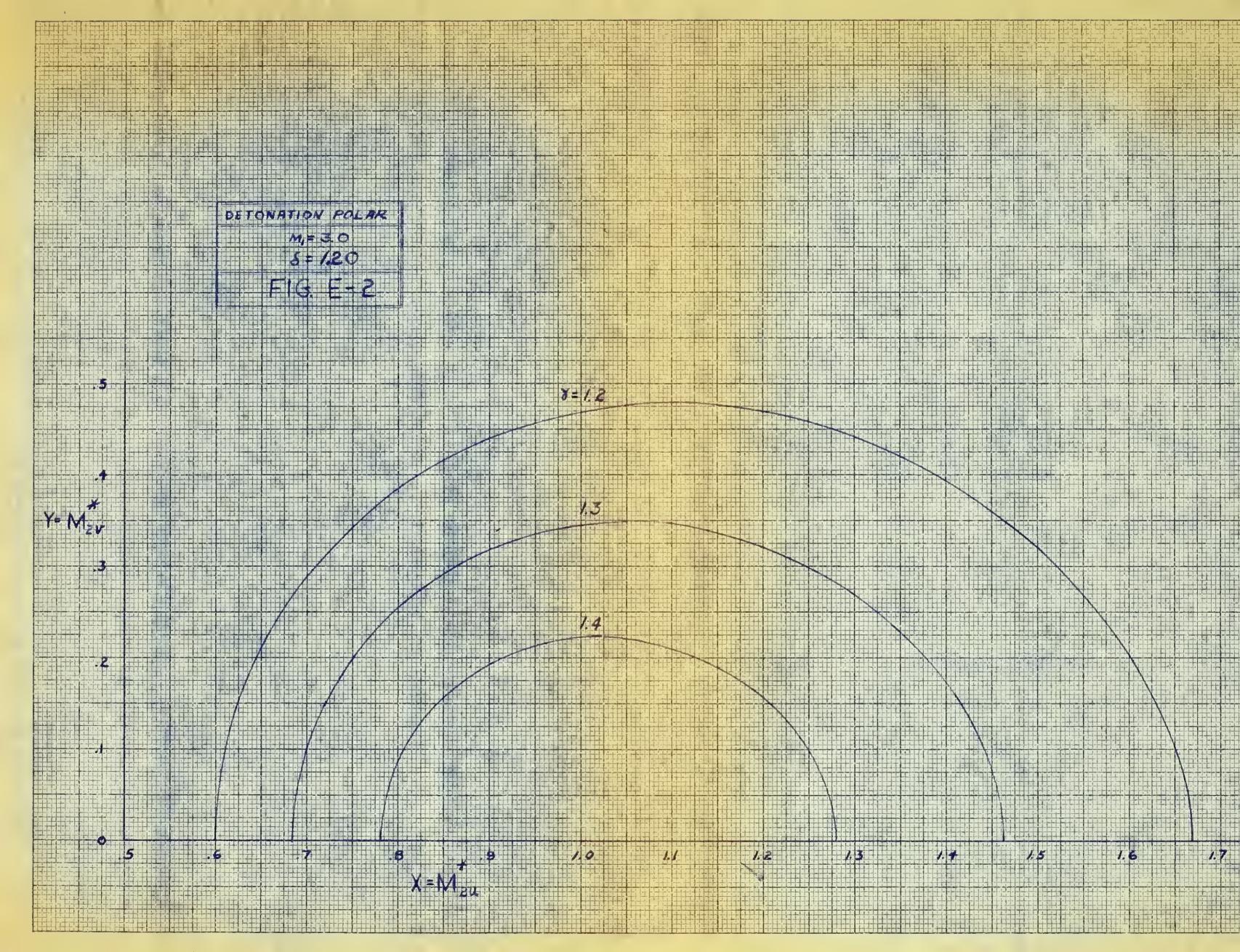






APPENDIX E





APPENDIX F

## all TOTAL

## COMPUTER PROGRAM

The data in Appendices G, H, and I was obtained by use of a Fortran (Formula translation) program on the U. S. Naval Postgraduate School Control Data Corporation 1604 digital computer. Table F-I is a list of variable names used in the program and their actual counterparts. Table F-II is an example of the program for a specific value of  $\mathcal{Y}=1.4$ . In this program the equations noted in Table II were solved for  $\mathcal{Y}=1.4$ .  $M_1$ ,  $\delta$ , and  $\kappa$  were allowed to assume ranges of values. Use of the program may be made for any value of  $\mathcal{Y}$ ,  $M_1$ , or  $\delta$  with only minor alterations.

## TABLE F-I

## TABLE OF FORTRAN VARIABLE NAMES

Fortran Symbol	Definition
ВУ	у
DEL	8
DELMAX	$S_{\mathrm{max}}$
EM1	$M_1$
EM1SQ	$M_1^2$
EM1ST	$M_1^*$
EM2	M <sub>2</sub>
EM2SQ	$M_2^2$
EM2STSQ	$(M_2^*)^2$
EM2U	M <sub>2u</sub>
EX	x
GAM	8
P21	P <sub>2</sub> /P <sub>1</sub>
PT21	$P_{T2}/P_{T1}$
SIGD	(degrees)
SIGR	(radians)
THETAD	θ (degrees)
THETAR	θ (radians)
T21	$T_2/T_1$
XMA	$x_{max}$ ( $Z_2$ value of Fig. 9)
XMI	$x_{min}$ (Z <sub>1</sub> value of Fig. 9)

```
PROGRAM OBLIQUE
    OPROGRAM TO CALCULATE PROPERTIES OF AN OBLIQUE DETONATION (LOOP 1BRANCH M1 = 1 TO 5 BY .5)
OCOMMON GAM, GPL, GMS, EM1, EM1ST, DEL, EX, BY, EM2U, EM2, DELMAX, 1THETAD, SIGD, P21, P121, XMI, IXMI, XMA, IXMA, A2, C5, EM1SQ, T21
     OCUMPION SI
      GPL
              = GAM+1.
      GMS = DO 120
                 GAM-1.
                     IEM1 = 10,50,5
      XEM1 = IEM1
      EM1
              = XEM1/10.
      EMISQ = EMI**2

EMIST = SQRTF(EMISQ * GPL/ (2. + EMISQ * GMS ))

DELMAX = (EMIST**2+1.)/(2.*EMIST)
      DDELMX
                  = DELMAX * 1000.
      IDELMX
                   = DDELMX
      WRITE OUTPUT TAPE 3,95
WRITE OUTPUT TAPE 3, 1
DO 60 IDEL= 1000, IDEL
                                        100
                IDEL= 1000, IDELMX, 40
      XDEL = IDEL
                =XDEL/1000.
      DEL
    CALL ZERO
IF (A2) 60, 40, 40
DO 50 IEX=IXMI, IXMA, 300
      XEX=IEX
      EX
                      XEX/10000.
 CALL CALCULATION CONTINUE

1F (C5) 50, 55, 55

550WRITE OUTPUT TAPE 3, 110, EM1, EM1ST, DELMAX, DEL, XMI, XMA, EX, 18Y, EM2U, EM2, THETAD, SIGD, P21, PT21, T21

50 CONTINUE
     WRITE OUTPUT TAPE 3, 57
      CONTINUE
950FORMAT (1H1 45X
112H GAMMA = 1.4,
1000FORMAT (119H M1
                                   29H LOOP BRANCH (M1 FROM 1 TO 5) //
                                   M2 M1*
                                                DELMAX DEL
                                                                         XMIN
                                                                                      XMAX
                                                                                                 X(M2U*)
                                            THETA
                                                                                       PTR21
     1M2V*)
                   M2U
                                                                           PR21
                                                                                                        TR21
     FORMAT (F5.1, 2F8.4, F5.2, 4F8.4, 2F9.4, 2F8.4, 2F9.4,
      CONTINUE
END FILE
      STOP
      END
      SUBROUTINE ZERO
    OCOMMON GAM, GPL, GMS, EM1, EM1ST, DEL, EX, BY, EM2U, EM2, DELMAX, 1THETAD, SIGD, P21, PT21, XMI, IXMI, XMA, IXMA, A2, C5, EM1SQ, T21
     THETAD, SIGD, P
A1 = DELMAX/DEL
A2 = A1 ** 2 -
     IF (A2) 35,
A3 = 0.
G0 TO 31
A3 = SQRTF
                   35, 29, 30
 29
                          (A2)
      XMI = A1 - A3
      XMA = A1+ A3

XXMI = XMI * 100.

IXXMI = XXMI

IXMI = IXXMI * 100

XXMA = XMA *
                                 *10000.
      IXMA
                   = XXMA
     RETURN
      END
      SUBROUTINE CALCU
    46
      BY
               = 0.0
      THETAR = 0.0
      THETAD = 0.0
```

```
SIGD = 90.0

GO TO 42

40 BY = SQRTF(C5)

THETAR = ATANF (BY/EX)

THETAD = THETAR * 57.2958

WI = EMIST/ (BY * SQRTF(DEL))

SIGR = ATANF( WI - EX/BY)

SIGD = SIGR * 57.2958

42 EM2STSQ = EX **2 + C5

EM2 = SQRTF ((2.* EM2STSQ) / (GPL - GMS * EM2STSQ))

EM2U = EM2 * COSF(THETAR)

EM2SQ = EM2 ** 2

DI = I. + EMISQ * GMS/2.

D2 = I. + EM2SQ * GMS/2.

T2I = (DEL ** 2) * (DI/D2)

D3 = SQRTF (T2I)

D4 = EM1 * EM2U

P2I = (EMISQ - D4 * D3) * D3 / (D4 - EM2SQ * D3)

PT2I = P2I * (D2/DI) ** (GAM / GMS)

45 RETURN

END
```

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THEORETICAL INVESTIGATIONS OF THE PROPERTIES
OF OBLIQUE DETONATION WAVES

bу

Philip 'F' Gibber

APPENDICES G, H, and I



Sibber, Philip 'F'

APPENDIX G

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/

M1.555555555555555555555555555555555555	M1* 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646	DELMAX DEL 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00 1.0487 1.00	XMIN •7328 •7328 •7328 •7328 •7328 •7328 •7328 •7328 •7328 •7328 •7328 •7328 •7328 •7328 •7328 •7328 •7328	XMAX 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646	X(M2U*) .7400 .7700 .8000 .8300 .8600 .9200 .9500 .9500 .9800 1.0100 1.0700 1.1300 1.1600 1.1600 1.12200 1.2500 1.2500 1.3400	Y (M2V*) .0498 .1093 .1415 .1634 .1790 .1973 .2014 .2027 .2013 .1975 .1912 .1827 .1719 .1587 .1431 .1252 .0815 .0263	M2U •7088 •7413 •7741 •8074 •8410 •87516 •9446 •9801 1•0528 1•0528 1•0528 1•1278 1•2456 1•2885 1•2885 1•37158 1•4614	M2 -7104 -7487 -7861 -8229 -8590 -87009 -87009 -87009 -9656 -9	THETA SIGMA 3.8469 85.4450 8.0791 79.5837 10.0276 75.9337 11.1377 73.0030 11.7607 70.4630 12.0544 68.1750 12.1064 66.0646 11.9711 64.0866 11.9711 64.0866 11.9711 60.4157 10.7504 58.6855 10.1336 57.0079 9.4304 55.3729 8.6476 53.7726 7.7896 52.2002 6.8592 50.6496 5.8578 49.1156 4.7855 47.5935 3.6410 46.0786 2.4220 44.5668 1.1246 43.0537	PR21 2.4418 2.3725 2.3033 2.2340 2.1648 2.0953 1.9570 1.88185 1.6808 1.6418 1.68108 1.6412 1.4030 1.3337 1.2650 1.1260 1.0567	PTR21 •9374 •9492 •9492 •9651 •9659 •9786 •9786 •9851 •9851 •9981 •9981 •9981 •9981 •9981 •9988 •9998 •9998	TR21 1.3171 1.3038 1.2905 1.2773 1.2498 1.22498 1.2228 1.2280 1.1937 1.16495 1
1.5 1.5 1.5 1.5 1.5 1.5	1.3646 1.3646 1.3646 1.3646 1.3646 1.3646 1.3646	1.0487 1.04 1.0487 1.04 1.0487 1.04 1.0487 1.04 1.0487 1.04 1.0487 1.04 1.0487 1.04 1.0487 1.04	• 8787 • 8787 • 8787 • 8787 • 8787 • 8787 • 8787 • 8787	1.1380 1.1380 1.1380 1.1380 1.1380 1.1380 1.1380 1.1380	.8800 .9100 .9400 .9700 1.0000 1.0300 1.0600 1.0900 1.1200	.0124 .0568 .0725 .0796 .0809 .0775 .0695 .0564	.8608 .8950 .9297 .9649 1.0007 1.0370 1.0739 1.1115	.8609 .8968 .9325 .9682 1.0039 1.0399 1.0762 1.1130 1.1503	.8076 88.4488 3.5725 82.4399 4.4122 79.6740 4.6907 77.7987 4.6251 76.5427 4.3009 75.8863 3.7510 75.9686 2.9620 77.1915 1.7939 80.8621	2.0373 1.9653 1.8933 1.8213 1.7493 1.6772 1.6052 1.5332 1.4612	•9003 •9023 •9040 •9052 •9061 •9066 •9066 •9062 •9053	1.3659 1.3510 1.3510 1.3207 1.3052 1.2894 1.2734 1.2569 1.2401

M2222222222222222222222222222222222222	M1* 1.63330 1.63330 1.63330 1.63330 1.633330 1.633330 1.633330 1.633330 1.633330 1.633330 1.633330 1.633330 1.633330 1.633330 1.633330 1.633330 1.633330 1.633330 1.633330	DELMAX DEL 1.1227 1.00	6124 6124 61	XMAX	Y(M2V#) .1658 .10657 .125763 .25763 .25763 .33564623 .3356463 .3	M28783 •648147088215487232946777881494548723294677788149467773885 •99264467777885 •9926467777885 •99264677778816626246 •9926467777881662626246 •9926467777881662626246 •9926467777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •992646777881662626246 •9926467778816662626246 •9926467778816662626246 •992646777888662626246 •9926467888662626246 •9926467888662626246 •9926468866262626246 •99264688662626262626246 •992646886626262626262626262626262626262626	•6246 •766648 •766648 •766648 •884449 •9937069 •9937069 •10125889 •101471528 •1014718	THETA SIGMA 6.9934 85.7064 14.3067 80.4282 17.7700 74.4639 21.2169 72.1669 22.0805 70.1024 22.0805 68.2031 22.8853 64.7495 22.9734 63.1486 22.9734 63.1486 22.9734 64.7495 22.9735 54.5564 22.97262 61.6109 22.7262 67.55.9047 22.4398 53.2493 22.91.055 55.9047 22.92.4398 53.2493 22.92.4398 53.2493 22.9398 53.2493 22.94398 53.297 19.2267 53.23 54.5564 19.2267 53.23 54.5564 19.2267 53.23 54.5564 19.2267 53.23 54.5564 19.2267 53.23 54.229 21.1055 53.23 54.229 21.1055 53.23 54.229 21.1055 53.23 54.23 19.2267 53.236.5769 16.9120 48.0705 17.7289 49.3385 16.9120 48.0705 17.7289 49.3385 16.9120 48.0705 17.7289 49.3385 16.9120 48.0705 17.7289 49.3385 16.9120 48.0705 17.7289 49.3385 16.9120 48.0705	PR 43 23 5 6 7 8 9 1 2 3 4 5 6 8 9 1 2 3 4 5 6 7 8 9 1 2 3 4 5 6 7 8 9 1 2 3 4 5 6 7 8 9 1 2 3 4 5 6 7 8 9 1 2 3 4 5 6 7 8 9 1 2 3 4 5 6 7 8 9 1 2 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3 3	PTR233939630976531951465265728644500 • 775446630976531951465263196579893644652631196579893644500 • 888944652631116572864450 • 99900 • 99000 • 990000 • 99000 •	TR21 1.6829 1.6650 1.6290 1.6290 1.6290 1.5745 1.55389 1.55389 1.55389 1.55389 1.4459 1.4459 1.44645 1.44645 1.4272 1.43870 1.33717 1.33717 1.2925 1.2925 1.2925 1.2927 1.1228 1.
222222222222222222222222222222222222222	1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330 1.6330	1.1227 1.04 1.1227 1.04	6729   67	4861       6800         4861       7100         4861       7400         4861       8000         4861       8300         4861       8600         4861       8600         4861       9200         4861       9200         4861       9800         4861       9800         4861       10100         4861       10700         4861       10700         4861       12200         4861       2500         4861       2800         4861       3100         4861       3400         4861       3400         4861       3400         4861       4000         4861       4000         4861       4000         4861       4000         4861       4000	.06445 .18924 .18924 .2474 .2274 .2274 .23951 .31186 .31186 .3316 .3316 .3316 .3316 .3316 .3316 .2276	.6464 .67118 .77108 .77708 .77708 .81495 .91409 .91	.7339 .7744 .8134 .81318 .81318 .9234 .99360 1.0721 1.1805 1.1805 1.2531 1.2531 1.25365	5.4348 85.9831 11.4985 80.7953 14.3642 77.5910 16.0941 75.0372 17.1843 72.8416 17.8550 70.8813 18.2268 69.0911 18.3739 67.4319 18.3739 67.4319 18.3736 64.4131 17.8838 63.0244 17.4931 61.7042 17.0142 60.4472 17.0142 60.4472 16.4568 59.2507 15.8278 58.1144 17.4931 55.1029 12.6740 54.2625 11.7329 53.5341 10.7290 52.9517 9.6585 52.5697 8.5158 52.4789 7.2913 52.8411 5.9687 53.9751 4.5135 56.6130 2.8214 63.0106	4.0608 4.0608 3.9608 3.9608 3.9732 3.1099	• 7083 • 7163 • 7242 • 7328 • 7398 • 7475 • 7628 • 77628 • 77638 • 77638 • 77638 • 77638 • 77638 • 7968 • 8089 • 8089 • 8187 • 82602 • 8359 •	1.7955 1.7765 1.7765 1.7765 1.7765 1.7765 1.7385 1.7194 1.7002 1.6809 1.6420 1.6420 1.6225 1.6028 1.5631 1.5631 1.5631 1.5631 1.5430 1.55227 1.5023 1.4607 1.4395 1.44607 1.4395 1.4395 1.4396 1.3739 1.3791 1.3792 1.3279 1.3279 1.3279 1.3279 1.3279 1.32792 1.2535
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2.0 2.0 2.0 2.0 2.0	1.6330 1.6330 1.6330 1.6330 1.6330	1.1227 1.12 1.1227 1.12 1.1227 1.12 1.1227 1.12 1.1227 1.12	.9331 1. .9331 1.	.0717 .9400 .0717 .9700 .0717 1.0000 .0717 1.0300 .0717 1.0600	.0239 .0481 .0537 .0486 .0290	•9293 •9645 1•0003 1•0366 1•0734	.9296 .9657 1.0017 1.0377 1.0738	1.4541 87.7340 2.8363 85.2061 3.0721 84.3556 2.7002 84.5910 1.5647 86.5697	2.9896 2.8744 2.7592 2.6440 2.5288	<ul><li>6676</li><li>6684</li><li>6689</li><li>6688</li><li>6682</li></ul>	1.9252 1.9030 1.8805 1.8578 1.8348

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555555555555555555555555555555555555555	1.8257 1.8257	1.1867 1.04 1.1867 1.04	• 59 155	1.6907 1.6907	.6000 .6300 .6600 .7200 .7500 .7800 .8400 .8400 .9300 .9600 .9900 1.0200 1.0500 1.0500 1.0100 1.1700 1.2600 1.2600 1.2600 1.3200 1.3500 1.3500 1.4400 1.4400 1.4700 1.5300 1.6500 1.6500 1.6500 1.6500 1.6500 1.6800	088333081832791597718941261851547101373 0883139081832791597718941261851547101373 0883139081832791597718941261851547101373 088313081832791597718941261851547101373 088313081832791597718941261851547101373 088313081832791597718941261851547101373 088313081832791597718941261851547101373	•5653 •5969 •6613 •672710 •69270 •76511 •76510 •76511 •86002 •970974 •	.5714 8.3411 85.7732 .6219 16.2764 80.9917 .6696 20.0789 77.9515 .7153 22.3952 75.5110 .7592 23.8964 73.4030 .8017 24.8794 71.5131 .8431 25.5047 69.7798 .8836 25.8691 68.1653 .9233 26.0356 66.6450 .9624 26.0469 65.2012 1.0009 25.9334 63.8213 1.0391 25.7173 62.4955 1.0769 25.4148 61.2164 1.1145 25.0385 59.9781 1.1520 24.5976 58.7761 1.1823 24.0996 57.6067 1.22641 22.9530 55.3548 1.3016 22.3117 54.2686 1.3393 21.6286 53.2073 1.3772 20.9051 52.1708 1.4154 19.3397 50.1740 1.4932 18.4979 49.2172 1.5328 17.6156 48.2924 1.5731 16.6913 47.4049 1.6141 15.7229 46.5628 1.6559 14.7075 45.7775 1.6988 13.6414 45.0666 1.7428 12.5197 44.4566 1.7882 11.3362 43.9893 1.8352 10.0825 43.7339 1.8841 8.7475 43.8123 1.9354 7.3146 44.44603 1.9895 5.7562 46.1996 2.0472 4.0116 50.4825	6.66.01372616183726161837261618372616183755.461650506.66.66.66.67594.66.66.67594.66.67594.66.6759464.67594.67594.67594.67594.67594.67594.67594.67594.67594.6759460	• 5017 • 50107 • 50107 • 50109 • 60109 • 60	2.2849 2.2849 2.2883 77   449 2.2883 77   499 2.2079 2.18567 2.1079 3.10

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•0311 •1010 •1337 •1549 •1692 •1783 •1830 •1839 •1810 •1745 •1640 •1490 •1283 •0990 •0485	.0202 .1286 .1761 .2094 .2346 .2346 .2595 .2895 .29972 .29972 .29972 .29973 .29	.0701 .1618 .21524 .2524 .2524 .3073 .3257 .3273 .33873 .33973 .3
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81 74.7665 17 74.3267 71 74.1650 42 74.3442 70 74.9754 95 76.2680	37 88.8573 00 82.5619 35 79.5527 84 77.2464 50 75.3126 93 72.1158 66 72.1158 67 68.3800 99 67.3514 01 68.3814 01 68.38514 71 64.2946 71 64.2946 71 63.5697 71 63.5697 64 63.7300 64 63.7300 64 63.7300 64 63.7300 64 63.7300 64 63.7300 65 699 66 699	74.0293 57 72.2098 87 70.5520 67 69.0189 57 67.5864 39 66.2380 88 64.9622 01 63.7507 26 62.5981 72 61.5005
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2.6960 2.66664 2.6367 2.6068 2.5767 2.5161 2.4856 2.4547 2.4237 2.3923 2.3606 2.3285 2.2960 2.2630	2.5851 2.5570 2.55289 2.5007 2.4724 2.4724 2.4756 2.3871 2.3584 2.3584 2.3296 2.3296 2.2716 2.2716 2.2128 2.128 2.1230 2.0615 2.0924 2.0924 2.0933 1.9328 1.9328 1.8988	2.4375 2.4107 2.3839 2.3571 2.33032 2.32762 2.2220 2.1220

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12.3714 76. 12.1867 75. 11.8212 75. 11.2910 74.	4.7264 87. 11.2065 82. 14.1743 80. 15.9716 78. 17.1152 76. 17.8301 74. 18.2388 73. 18.4157 72. 18.4096 71. 18.2535 70. 17.9707 69. 17.9707 69. 17.5778 68. 17.0860 68. 16.5032 67. 15.8337 66. 15.0791 66. 15.0791 66. 14.2379 66. 15.2379 66. 11.1216 67. 9.8260 68. 8.3330 70. 6.5287 73. 4.0493 78.	19.6858 77. 21.1004 75. 21.1004 75. 22.0253 72. 22.6083 72. 22.9387 70. 23.0747 69. 23.0747 69. 23.0563 68. 22.9116 66. 22.3199 64. 22.6611 62. 21.8993 64. 21.8993 64. 21.8993 64. 21.8993 63. 21.8993 63. 21.8993 69.
1758 1395 1099 1093 1093 17045 17047 17214	61078867335915916738867335915916958475518719477	243483975440561 243483975440561 2817353288101107697247533555728 2434839754402043907247533555728 24348397544056804828533611754
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• 1933 • 1948 • 1962 • 1975 • 1988 • 1999 • 2008 • 2016 • 2026 • 2028 • 2028 • 2028 • 2024 • 2018 • 2009 • 1995	1978 2002 20025 2049 2072 2094 2116 21137 21158 2177 2195 2212 2224 22268 2227 22268 2227 22268 2227 2227 2	• 2051 • 2081 • 2081 • 2177 • 2217 • 2227 • 22336 • 2245 • 2255 • 2255 • 2263 • 2255 •
4.7355 4.6824 4.6291 4.5757 4.5222 4.4686 4.3666 4.3666 4.3666 4.2521 4.1975 4.0872 4.0872 4.0873 3.9753	4.5478 4.4968 4.4968 4.4968 4.4968 4.3947 4.39435 4.2969 4.137	4.3115 4.2625 4.1663 4.1669 4.1669 4.1669 4.1669 4.1669 4.1696 81997 3.8199 3.8199 3.8199 4.1629

GAMMA = 1.4					
M1	XMIN       XMAX       X(M2U*)         .4677       2.1381       .4700         .4677       2.1381       .5300         .4677       2.1381       .5600         .4677       2.1381       .6200         .4677       2.1381       .6200         .4677       2.1381       .6200         .4677       2.1381       .7400         .4677       2.1381       .7400         .4677       2.1381       .7700         .4677       2.1381       .8000         .4677       2.1381       .8000         .4677       2.1381       .8000         .4677       2.1381       .8000         .4677       2.1381       .8000         .4677       2.1381       .9500         .4677       2.1381       .9500         .4677       2.1381       .0100         .4677       2.1381       .1000         .4677       2.1381       .1000         .4677       2.1381       .1000         .4677       2.1381       .12200         .4677       2.1381       .12200         .4677       2.1381       .1200         .4677       2	Y(M2V*)	THETA 7.2603 87.9442 5126 38.9945 82.26334 7.2603 87.92234 55126 30.0068 79.2234 6364 33.3709 76.84121 7.452 36.8170 73.8008 7.960 37.6999 71.3806078 8451 38.5887 66.986678 8451 38.5887 66.98758 1.0301 38.6897 64.1477 1.07452 38.7691 65.676 9852 38.7691 65.676 9852 38.7691 65.676 1.185 38.2972 62.0159 1.1621 38.0110 60.8671 1.2058 37.3040 58.74693 1.2919 36.8957 55.4765 1.2919 36.8957 55.443368 1.5983 33.9068 51.43388 1.5983 33.9385 59.445366 1.5094 33.9912 55.4453636 1.5094 33.9927 46.5629 1.8299 30.5916 44.66375 1.4218 35.9912 55.445331 1.7354 330.9029 45.5629 1.88783 29.5916 44.6675 1.9276 28.91277 40.7589 1.88783 29.5916 44.6675 1.9276 28.91277 40.75803 1.7354 31.5351 47.695 2.1351 26.0311 39.7803 1.7354 31.5352 44.798 1.6891 33.7888 33.78960 2.1351 26.0311 39.7803 2.1961 22.4656 23.3683 2.7528 44.798 33.7860 2.24654 22.3655 38.7960 2.3644 22.38420 35.7695 2.4896 23.3641 22.8420 35.7695 2.4896 23.3641 22.8420 35.7695 2.4896 23.3641 22.8420 35.7695 2.4896 23.3641 22.8420 35.7695 2.4896 23.3641 22.8420 35.7695 2.4896 23.3641 22.8420 35.7695 2.4896 23.3641 22.8420 35.7695 2.4896 23.3641 22.8420 35.76991 2.4656 21.9863 33.7326 2.4656 21.9863 33.7326 2.4656 21.9863 33.7326 2.4656 21.9863 33.7326 2.4656 21.9863 33.7326 2.4656 221.9863 33.7326 2.4656 221.9863 33.7326 2.4656 221.9863 33.7326 2.4656 221.9863 33.7326 2.4656 231.1031 33.7326 2.4656 221.9863 33.7326 2.4656 221.9863 33.7326 2.4656 221.9863 33.7326 2.4656 221.9863 33.7326 2.4656 221.9863 33.7326 2.4656 221.9863 33.7326 2.4656 221.9863 33.7326 2.4656 23.97330 3.3641 22.8888 22.8888 22.8895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.8888 22.88895 3.3641 22.888895 3.3641 22.88880 3.3645 22.88880 3.3646 22.88880 3.3646 22.88880 3.3668 2776 276000000000000000000	107418529630741852963074185296307418 1074185299630741852963074185296307418 1187.29529630741852963074185296307418 1187.176.6.2963764318499517666.296376431839 1188.177.176.6.296376431849517666.296376431839 1188.177.176.6.296376431849517666.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.296376431839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.177.176.6.2963764331839 1188.176.1763764331849 1188.1763764431849 1188.1763764431849 1188.1763764431849 1188.1763764431849 1188.1763764431849 1188.1763764431849 1188.1763764431849 1188.1763764431849 1188.1763764431849 1188.1763764431849 1188.1763764431849 1188.176376444444433333334 1188.176476444444444444444444444444444444444	PTR21
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5923 6447 6947 7423 278826 299 100408 299 100408 299 100408 299 100408 299 100408 299 100408 2077 100408 100408 2077 100408	5748 6325 6325 7801 8710 87148 87148 97501 100838 100
4618 65.5911 2514 64.4655 9652 63.3822 6138 62.3370 2058 61.3264 7476 60.3480 2441 59.3999 6994 58.4808 1161 57.5898 1161 57.5898 1161 57.5898 4967 56.7268 8424 55.0863 4328 54.3113	6745 58.2736 1720 57.2833 6366 56.3133 0708 55.3620 4764 54.4285 8547 53.5118 2067 52.6115 5331 51.7270 8339 50.8586 1092 50.0065 3585 49.1714 5811 48.3546 7760 47.5577
16.717777766.36177777766.361777777766.3616.361	17.906 16.9501 16.973284 9501 16.273284 9506 17.284 17.284 17.284 17.284 17.284 17.284 17.284 17.284 18.9506 17.384 18.951 18.95
• 1339243 • 1339243 • 1457146050630853208233558007105459241 • 15516687308532082233358007105459241 • 166873335394800710542592442733 • 166873335394800710542592442733 • 16687333539480071054259241 • 17887335580071054259241 • 17887335800071054259241 • 1788735800071054259241 • 17887358000071054259241 • 1788735800007105459241 • 17887358000000000000000000000000000000000	• 13970 • 13970 • 14995 • 14995 • 16937720 • 16937720 • 16937720 • 16937720 • 16937720 • 17720 • 18610 • 17720 • 18610 • 17720 • 18610 • 19610 • 19610 • 19610 • 19620 • 2223395 • 2277888485 • 2223322 • 222332 • 2223332 • 222332 • 222332 • 222332 • 22332 • 2233
20997530741738381579110961689725387051406 923345677890011122222222 98264827890011122222222 98264826890011122222222 98264826890011122222222 982648267890011122222222 98264826789001112222222 9826482678900111222222222222222222222222222222222	2333455554321086307384825788475157747721256048 659384555554321086307384825788875157747721256048 659384555554321086307384825788875157747721256048 644.4444444444444444444444444444444444

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444444444444444444444444444444444444444	2.1381 2.1381	1.3029 1.20 1.3029 1.20	. 6628   1.5087   6628   6288   6288   6288   6288   6288   62888   62888   62888   62888   62888   62888   62	.7600 .7900 .8200 .8500 .8800 .9100 .9700 1.0000 1.0500 1.1500 1.1500 1.1500 1.2400 1.2400 1.2700 1.3300 1.3600 1.3900 1.4500 1.4800	• 2582 • 2891 • 3148 • 33518 • 33658 • 33955 • 33977 • 33977 • 3397 • 3397 • 3397 • 33937 • 33	7343 7679 8019 83612 90153 90153 101	.7756 18.7664 77.774 .8177 20.0984 76.027 .8587 20.9637 74.486 .8988 21.5000 73.0966 .9382 21.7915 71.827 .9770 21.8929 70.6582 1.0153 21.8420 69.5758 1.0532 21.6653 68.5718 1.0908 21.3821 67.6398 1.1281 21.0065 66.7778 1.1653 20.5489 65.9842 1.2024 20.0168 65.2618 1.2395 19.4152 64.6128 1.2395 19.4152 64.6128 1.3138 18.0148 63.5633 1.3511 17.2173 63.1849 1.3887 16.3528 62.9258 1.4265 15.4172 62.8118 1.3887 16.3528 62.9258 1.4265 15.4172 62.8118 1.5033 13.3021 63.1738 1.5425 12.0958 63.7808 1.5822 10.7586 64.8208 1.6227 9.2449 66.5092 1.6641 7.4630 69.2678 1.7065 5.1667 74.1648	13.8453 13.4681 13.4681 13.0910 12.7138 12.3367 11.9595 11.5823 11.9595 11.58280 10.4509 10.6966 10.4509 10.6966 10.6965 10.6966 10.6965 10.6966 10.69	• 1376 • 1376 • 13795 • 1433 • 14432 • 14485 • 14502 • 1533 • 1558 • 1558 • 15611 • 1623 • 1617 • 1623 • 1603 • 1574	5.3347 7775.3347 7775.2065 14785 147
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M1 * 1 * 1 * 1 * 1 * 1 * 1 * 1 * 1 * 1 *	XMIN	Y(M2V*)	M2	PR21	247025792468034680134567899000998764296272589977366338361924889446801345678990009987642725899773663383619248894444444433333333333333333333333333
4.5 2.1936 1.3247 1.04 4.5 2.1936 1.3247 1.04 4.5 2.1936 1.32247 1.04	. 4848	• 0883	. 4642 10 . 2116 86 . 9581 82 . 0771	22. 39. 39. 39. 39. 39. 39. 39. 39. 39. 39	5.04.884.95.06.16.16.16.16.16.16.16.16.16.16.16.16.16

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8593 8593 8593 8593 8593 8593	7510 7510 7510 7510 7510 7510 7510 7510	33333333333333333333333333333333333333	6331 6331 63331 63331 63331 63331 63331 63331 63331 63331 63331 63331 63331 63331 63331 63331 63331 63331	44444444444444444444444444444444444444
1.1637 1.1637 1.1637 1.1637 1.1637 1.1637	1.3315 1.3315 1.3315 1.3315 1.3315 1.3315 1.3315 1.3315 1.3315	1.4613 1.4613 1.4613 1.4613 1.4613 1.4613 1.4613 1.4613 1.4613 1.4613 1.4613	1.5796 1.5796 1.5796 1.5796 1.5796 1.5796 1.5796 1.5796 1.5796 1.5796 1.5796 1.5796 1.5796	1.6936 1.6936 1.6936 1.6936 1.6936 1.6936 1.6936 1.6936 1.6936 1.6936 1.6936 1.6936 1.6936 1.6936 1.6936
.8600 .9100 .9600 1.0100 1.0600 1.1100	.7600 .8100 .8600 .9100 .9600 1.0100 1.1100 1.1600 1.2100 1.2600 1.3100	.6900 .7400 .7900 .8400 .8900 .9400 .9900 1.0400 1.1400 1.1900 1.2400 1.2400 1.3400 1.3900 1.4400	.6400 .67400 .7400 .7900 .8900 .9900 1.0900 1.1400 1.1900 1.2900 1.3400 1.3400 1.4900 1.4900	.6000 .6500 .7000 .7500 .8500 .9000 1.0500 1.1500 1.2500 1.2500 1.3500 1.4500 1.4500 1.5500 1.5500 1.6500
.0145 .1129 .1426 .1514 .1435 .1154 .0333	.0714 .1747 .2258 .2577 .2774 .2871 .2881 .2804 .26346 .1894 .1088	.0661 .1997 .2694 .3094 .3414 .3678 .3867 .3868 .3868 .3868 .3199 .225 .225	.0805 .224868 .2248687 .35897 .445667 .445667 .445667 .445669 .445669 .445336 .445336 .43737 .45669 .45697 .477 .477 .477 .477	•195 •195 •195 •3887 •4887 •4887 •4887 •4918 •4918 •5548 •55
.8385 .8959 .9545 1.0144 1.0756 1.1383 1.2024	.7301 .7858 .8425 .9006 .9599 1.0205 1.0826 1.1462 1.2113 1.2782 1.3468 1.4172	.6567 .7112 .7669 .8238 .8820 .9415 1.0648 1.1237 1.1943 1.2616 1.3308 1.44751 1.4751 1.5505 1.6283	.6056 .6595 .7145 .7768 .8872 .9474 1.0092 1.0726 1.137436 1.2730 1.3436 1.4912 1.5684 1.73166	.5655 .6189 .67353 .7293 .7864 .8449 .96634 1.09427 1.229973 1.429973 1.429971 1.52477 1.668734 1.95521
.8386 .9027 .9649 1.0257 1.0854 1.1444 1.2029	.8711 .9360 .9991 1.0610 1.1219 1.1822 1.2421 1.3020 1.3619 1.4221	.8090 .8781 .9446 1.0094 1.0729 1.1355 1.1975 1.2591 1.3206 1.3823 1.4444	.7705 .8433 .9131 .9807 1.0466 1.115 1.1755 1.2391 1.3025 1.3060 1.4298 1.4940 1.5590 1.6249 1.6918	.7441 .8205 .8934 .9637 1.0992 1.1654 1.2310 1.2965 1.3619 1.4277 1.4939 1.6288 1.6978 1.7683 1.8403
7.0735 8.4466 8.5275 7.7101 5.9348	12.1709 14.7085 15.8141 16.1148 15.8707 15.2068 14.1776 12.7860 10.9730 8.5491 4.7475	15.1050 18.5695 20.2458 20.9873 21.1432 20.8902 20.3261 19.5063 18.4593 17.1930 15.6951 13.9262 11.7972 9.0918	18.0104 21.9761 23.9413 24.8907 25.2248 25.1454 25.17663 24.1554 24.1554 23.3544 22.3677 19.9971 18.5688 15.13.0105 10.4356	20.9228 25.1628 27.287 28.7475 28.7475 28.4603 28.4603 27.927.32 27.27.31 27.27.31 21.59788 17.385 15.4958 117.335
89.2963 84.3149 82.5099 81.6699 81.7048 82.9593 87.8417	86.6917 82.1319 79.4668 77.5158 76.6206 74.6988 74.1394 73.7833 73.9349 74.6105 76.9028 81.6969	87.3268 81.6771 78.52725 76.2415 776.20843 71.20846 70.1189 69.1784 68.4853 68.666 68.5729 69.729 79.2954	36. \$227 77. \$423 77. \$443 75. 44295 73. 4295 69. 7804 69. 7804 66. 4295 68. 3044 66. 4295 68. 3044 66. 4295 68. 3084 66. 4295 68. 3084 66. 4295 68. 3084 68. 3	80.7278 77.4085 77.
138.8144 130.8734 122.9323 114.9913 107.0503 99.1093 91.1682	158.1451 150.4310 142.7168 135.0027 127.2886 119.5744 111.8603 104.1461 96.4320 88.7179 81.0037 73.2896	172.0759 164.5887 157.1014 149.6142 142.1269 134.6397 127.1524 119.6652 112.1779 104.6907 97.2034 89.7162 82.2289 74.7417 67.2544 59.7672	182.4673 175.2070 167.9466 160.6862 153.4259 146.1655 138.9051 131.6448 124.3844 117.1240 109.8637 102.6033 95.3430 88.0826 80.8222 73.5619 66.3015 59.0411 51.7808	190.9983 183.9648 176.9313 169.8978 162.8643 155.8309 148.7974 141.7639 134.7304 127.6970 120.6635 113.6300 106.5965 99.5630 92.5296 85.4961 78.4626 71.4291 64.3956 57.3622 50.3287 43.2952
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69.0768 67.7499 66.4227 65.0949 63.7664 62.4372 61.1070	67.1330 65.8451 64.55570 63.2686 61.9798 60.6907 59.4011 58.1109 56.8200 55.5282 54.2353 52.9408	64.4355 63.1860 61.9364 60.6867 59.4365 55.4365 55.6365 55.6345 55.6365 55.44823 51.93771 49.4232 48.1614 46.9124	61.2962 60.08536 58.86522 58.86522 55.4.2389 55.4.2389 55.4.2379 55.4.2389 55.4.2379 55.4.2379 55.4.2379 55.4.2379 55.4.2379 55.4.2379 57.449 57.3379 47.9749	57.959 59.28 59.29 50.49 5

APPENDIX H

M1 1.55 1.55 1.55 1.55 1.55 1.55 1.55 1.	M1* DELMAX DEL 1.3909 1.0549 1.00	XMIN XMAX .7190 1.3909 .7190 1.3909	7200 7500 7800 8100 8400 8700 9300 9300 9600 9900 1.0200 1.0500 1.0800 1.1100 1.1400 1.1700 1.2000 1.2300 1.2600 1.2900 1.3200 1.3500	M2V*) 0197 0197 06953 1040 7271 1408 7591 1657 1837 8240 8570 2060 2119 2150 9577 9920 2154 2154 2154 10266 21942 10432 10617 2028 10972 10427 10409 0427 0120 104844	.8078 .8435 .8786 .9132 .9474 .9814 1.0152 1.0489	THETA SIGMA 1.5633 88.3223 7.8953 80.7820 10.2348 77.0180 11.5633 74.0765 12.3362 71.5580 12.7442 69.3058 12.8898 67.2390 12.8853 65.3095 12.6218 63.4858 12.2774 61.7456 11.8224 60.0729 11.2714 58.4551 10.6352 56.8825 9.9216 55.3470 9.1365 53.8420 8.2837 52.3619 7.3658 49.4567 5.3393 48.0232 4.2303 46.5972 3.0555 45.1752 1.8121 43.7537 .4964 42.3290	PR21 2.4109 2.3478 2.2847 2.2847 2.1585 2.0954 2.0952 1.9692 1.9692 1.7169 1.6538 1.7809 1.6597 1.6538 1.52753 1.2122 1.1491 1.0860 1.0229	PTR21 •9325 •9325 •9384 •9504 •9554 •9655 •9785 •97857 •9887 •9887 •9887 •99814 •9997 •9997 •9999	TR21 1.2470 1.2375 1.2279 1.2182 1.2085 1.1987 1.1888 1.1788 1.1687 1.1584 1.1687 1.1268 1.160 1.1268 1.160 1.049 1.0936 1.0936 1.0936 1.0937 1.09327 1.0952
1.5 1.5 1.5 1.5 1.5 1.5 1.5	1.3909 1.0549 1.04 1.3909 1.0549 1.04	.8443	.8800 .9100 .9400 .9700 1.0000 1.0300 1.0600 1.0900 1.1200 1.1500	0304	.8334 .8686 .9034 .9379 .9723 1.0065 1.0408 1.0752 1.1098 1.1449 1.1804 1.2165	2.0464 86.6177 4.6393 81.6051 5.6682 78.7455 6.1217 76.6211 6.2252 74.9637 6.0779 73.6895 5.7325 72.7930 5.2178 72.3312 4.5448 72.4454 3.7035 73.4449 2.6332 76.1104 .9006 84.2400	2.0660 2.0004 1.9348 1.8691 1.8035 1.7379 1.6723 1.6067 1.5411 1.4755 1.4099 1.3442	.9003 .9029 .9051 .9071 .9087 .9099 .9107 .9112 .9112 .9108	1.3101 1.2996 1.2888 1.2780 1.2670 1.2558 1.2444 1.2329 1.2210 1.2090 1.1966 1.1838

M1000000000000000000000000000000000000	M1* 1.6956 1.6956 1.69566 1.69566 1.69556 1.69556 1.69556 1.69556 1.69556 1.69556 1.69556 1.69556 1.69556 1.69556 1.69556	DELMAX DEL 1.1427 1.0 1.1427 1.0	5898 5898 5898 5898 55898 5588988 558898 558898 558898 558898 558898 558898 558898 558898 5588988 558898 558898 558898 558898 558898 558898 558898 558898 5588988 558898 558998 55898	XMAX 1.6956 1.6956 1.69556 1.69556 1.699556 1.699556 1.699556 1.699556 1.699556 1.699556 1.699556 1.699556	X(M2U*) .5900 .6200 .6800 .7400 .7700 .8300 .88600 .89200 .9500 .9800 1.0400 1.1600 1.1600 1.1900 1.1600 1.1900 1.1600 1.1900 1.1600 1.1900 1.1900 1.1900 1.1900 1.1900 1.1900 1.1900 1.1900 1.1900 1.1900 1.1900 1.1900 1.1900	Y(01396 01396 015558 015568 01	M20 •56426 •659426 •659426 •67275 •815374 •815374 •815374 •9150818	•6591 •7034 •7458 •78638 •86485 •9394 •97515 1•0467 1•1508 1•125374 1•25374 1•35904 1•4609	THETA SIGM 1.3471 89.28 14.0902 81.76 18.3649 78.37 20.8729 75.67 20.8729 75.67 21.38 24.712 67.81 24.7073 66.19 24.7152 63.17 24.7152 63.17 24.7152 63.17 24.7152 63.17 24.7152 63.17 24.7152 63.17 24.3657 60.33 24.3657 60.33 24.3657 60.37 24.3657 60.33 22.6824 55.26 22.6824 55.27 23.6568 57.75 23.6568 57.75 23.6568 57.75 24.8980 53.96 22.6824 56.45 22.6824 56.45 23.6568 47.99 23.6568 47.99 24.8980 53.96 21.4980 46.82 21.4980 46.82 21.4	10 73 4.2986 4.29866 4.29866 4.20866 4.0238866 4.0238866 3.47865 3.478665 3.47866	PTR21 •7007 •7110 •7215 •72263 •732231 •77857 •78644 •77857 •81299 •	TR21 1.5277 1.52147 1.52147 1.52168 1.47641 1.476414 1.4388 1.4259 1.4387 1.33741 1.33741 1.33949 1.33949 1.22679 1.22
2.0 2.0 2.0 2.0 2.0 2.0 2.0	1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956	1.1427 1.0 1.1427 1.0 1.1427 1.0 1.1427 1.0 1.1427 1.0 1.1427 1.0 1.1427 1.0	0	1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956	1.4600 1.4900 1.5200 1.5500 1.5800 1.6100 1.6400 1.6700	• 2827 • 2574 • 2296 • 1989 • 1653 • 1283 • 0875 • 0423	1.6140 1.6586 1.7042 1.7509 1.7989 1.8484 1.8995	1.6440 1.6832 1.7235 1.7653 1.8087 1.8542 1.9022 1.9533	10.9598 39.80 9.8018 38.61 8.5884 37.41 7.3141 36.19 5.9723 34.96 4.5551 33.71 3.0526 32.43 1.4527 31.13	23 1.7225 1.6305 07 1.5385 54 1.4465 35 1.3545 20 1.2625 72 1.1705	9820 9869 9910 9943 9968 9986 9996	1.1385 1.1228 1.1068 1.0903 1.0733 1.0556 1.0371 1.0176
222222222222222222222222222222222222222	1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956	1.1427 1.0 1.1427 1.0	55555555555555555555555555555555555555	1.5539 1.55539 1.55539	.6500 .6800 .7100 .7400 .7700 .8300 .88600 .9200 .9500 .9500 .9500 .9100 1.0400 1.1600	• 1542 • 152170 • 152170	•6237 •6559 •7189 •7513 •7839 •8160 •8177 •9863 •9517 •9863 1•05257 1•05257 1•1653 1•23780 1•23780 1•3557 1•4773 1•5621 1•56259 1•6508 1•6508 1•6969 1•7444	.7140 .7549 .7945 .8330 .8705 .9072 .9433 .9788 1.0186 1.04830 1.1172 1.1852 1.1852 1.2531 1.2531 1.3563 1.3913	5.7555 86.29 12.6284 78.07 17.7573 75.59 18.9898 73.46 19.7691 71.56 20.2297 69.82 20.4535 68.21 20.4535 68.21 20.4941 66.70 20.3886 65.27 20.1631 63.91 19.8370 62.62 19.4246 61.37 18.9366 69.03 17.7645 57.93 17.0911 56.88 18.3812 57.93 17.0911 56.88 16.3642 57.93 17.0911 56.88 16.3642 57.93 17.0911 56.88 16.3642 57.93 17.0911 56.88 16.3642 57.93 17.0911 56.88 16.3642 57.93 17.0911 56.88 16.3642 57.93 17.0911 56.88 16.3642 57.93 17.0911 56.88 16.3642 57.93 17.0911 56.88 16.3642 57.93 17.7531 54.33 3.1638 59.50 9469 77.18	70 23 3.9358 3.9358 3.9358 3.9358 3.9358 3.9358 3.9358 3.9358 3.9358 3.9358 3.9358 3.9369 3.94827 3.9486 3.9487 3.9786 3.9786 3.9787 3.	•6986 •6986 •71210 •77	1.6342 1.62076 1.62076 1.598074 1.558074 1.558074 1.558074 1.5513946 1.5513946 1.5513941 1.44295 1.44295 1.44295 1.44295 1.44295 1.4429777 1.442977 1.442977 1.442977 1.442977 1.442977 1.442977 1.4429777 1.442977 1.442977 1.442977 1.442977 1.442977 1.442977 1.4429777 1.442977 1.442977 1.442977 1.442977 1.442977 1.442977 1.4429
2.0000000000000000000000000000000000000	1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956	1.1427 1.0 1.1427 1.0	7124 7124 7124 7124 7124 7124 7124 7124	1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036 1.4036	.7200 .7500 .7800 .8100 .8400 .8700 .9000 .9300 .9600 .9900 1.0500 1.0500 1.1100 1.1700 1.2300 1.2300 1.2600 1.3200 1.3500 1.3500	•0607 •1317 •1715 •1999 •2377 •2592 •2592 •2688 •2688 •2688 •2688 •2688 •2688 •2688 •2688 •2118 •1720 •1151 •1751	.6955 .7274 .7596 .7591 .8250 .8581 .8915 .9254 .9939 1.0259 1.0288 1.0640 1.0997 1.1358 1.2469 1.2846 1.2846 1.2846 1.4851	• 9253 • 9606 • 9954 1• 0299 1• 0642 1• 0982 1• 1323 1• 1662 1• 2003 1• 2345	4.8203 86.18 9.9565 81.50 12.4020 78.61 13.8638 76.32 14.7617 74.37 15.2836 72.66 15.5335 71.12 15.5756 69.72 15.4522 68.43 15.1925 67.26 14.8173 66.19 14.3415 65.22 13.7757 64.35 14.3415 65.22 13.7757 64.35 14.3415 62.98 14.3415 62.98 14.3415 62.98 14.3415 62.98 14.3415 62.98 14.3415 62.98 14.3415 62.98 14.3415 62.98 14.3415 62.98 13.7757 64.35 13.1274 63.60 12.4013 62.51 10.7232 62.23 9.7685 62.19 8.7294 62.49 7.5933 63.27 6.3356 64.80 4.9008 67.65 3.1148 73.37	60 3.7159 20 3.6165 41 3.5172 82 3.4178 35 3.3184 21 3.2191 06 3.1197 89 3.0203 2.9210 2.8216 2.7223 63 2.6229 42 2.5235 12 2.4242 13 2.3248 60 2.1261 53 2.0267 65 1.9273 85 1.8280 1.7286	.6757 .6816 .6874 .6986 .7089 .7183 .7183 .7265 .7333 .7361 .7333 .7412 .7423 .7423 .7423 .7423 .7423 .74357	1.7392 1.7251 1.7251 1.7251 1.6968 1.6968 1.6826 1.6538 1.6248 1.6393 1.6248 1.65953 1.55652 1.55800 1.55800 1.5587 1.5587 1.5953 1.595
2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0 2.0	1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956 1.6956	1.1427 1.1 1.1427 1.1 1.1427 1.1 1.1427 1.1 1.1427 1.1 1.1427 1.1 1.1427 1.1 1.1427 1.1 1.1427 1.1 1.1427 1.1	2	1 · 22 25 1 · 22 25	.8200 .8500 .8800 .9100 .9400 .9700 1.0000 1.0300 1.0600 1.0900 1.1200 1.1500 1.1800 1.2100	.0233 .0893 .1182 .1364 .1480 .1571 .1558 .1510 .1424 .1299 .1124 .0880 .0485	.8006 .8333 .8664 .8997 .9334 .9674 1.0019 1.0366 1.0718 1.1435 1.1800 1.2171 1.2547	.8009 .8379 .8741 .9098 .9449 .9797 1.0141 1.0484 1.0827 1.1169 1.1512 1.1857 1.2205	1.6302 88.29 5.9950 83.23 7.6514 80.70 8.5251 78.85 8.9472 77.40 9.0573 76.25 8.9288 75.37 8.6040 74.76 8.1062 74.43 7.4446 74.45 6.6134 74.92 5.5830 76.03 4.2654 78.22 2.2942 82.95	22 3.2804 3.1774 16 3.0743 17 2.9713 56 2.8682 72 2.7652 38 2.6621 94 2.5591 94 2.4561 73 2.3530 90 2.2500 45 2.1469	.6573 .6605 .6634 .6660 .6683 .6702 .6718 .6729 .6736 .6736 .6734 .6726	1.8309 1.8158 1.8007 1.7854 1.7700 1.7545 1.7388 1.7230 1.7069 1.6907 1.6742 1.6575 1.6405 1.6231

M1	1.2226   .00   .	XMIN XMAX 1.9261 .5192 1.9261 .	X ( M20 * )	Y ••••••••••••••••••••••••••••••••••••	767290412635092805559821550181182442086685789627 9472578136926350928075593715811824442086685789627 955818136926350928075593715811824442086685789627 95581812635092805598215501811824442086685789627 95781364685789627 95781364442086685789627 95781364445086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 95781364442086685789627 9578136444442086685789627 9578136444442086685789627 95781364444420866685789627 9578136444444444444444444444444444444444444	M2	114837261504937261504938261504938271604938271606666666665555555554444444443333333322222221111111111	PT.44708928669422449656839644322085908189157869699898989898989989898989898989898989	TR86224 1.885554567888999998765211.88535810.336999998765336999999876533699999987654311.87777766664314544542068653316799078411.84438753316799078411.84433333333333333333333333333333333
2.5 1.9261 2.5 1.9261	1. 2226	• 5575 1 • 7937 • 5575 1 • 7937	•5900 •6200 •6500 •6800 •7100 •7700 •8800 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •98000 •980000 •98000 •9	623142119058151142424365870669371300073927 01223334444445555555555555555555555555555	347335102879660817844733517396598541 5569279140287966178449955635403317396598541 -556677759261784999556354033317396598541 -5667776128811.11.11.11.11.11.11.11.11.11.11.11.11	5355 5901 16.9852 82.0995 6410 21.6649 79.0136 6890 24.4210 76.5978 7347 26.1870 774.5343 8208 828.0994 71.0178 8208 828.0994 71.0178 8208 828.0994 71.0178 8208 828.8979 67.9953 9408 28.8877 66.6076 9791 28.8361 65.2831 1.0167 28.6780 64.0119 1.0537 28.4320 62.7866 1.0902 28.1119 61.6009 1.12642 27.72900 59.33381 1.2331 26.2718 57.1710 1.2683 25.7009 56.1268 1.3034 25.0933 55.1037 1.3384 24.4511 54.1004 1.3735 23.7761 53.1159 1.4086 23.3316 52.1495 1.4986 23.3316 50.2707 1.5504 19.9335 48.4675 1.5504 19.9335 48.4675 1.5504 19.9335 48.4675 1.5504 19.9335 48.4675 1.5504 19.9335 48.4675 1.5504 19.9335 48.4675 1.5504 19.9335 48.4675 1.5504 19.9335 48.4675 1.5865 19.0709 47.5980 1.66973 16.2760 45.1594 1.7353 11.9696 42.6589 1.89391 1.9838 8.1330 42.4949 2.0306 2.0798 2.1321 2.1884	259937158260481593715826048159371158260471058260481593715826048159371632087532087532097542197648260471596365316666666666666666666666666666666	694198903839754433344443183664760904950333020 • 44888703839754433344443183664760904950333020 • 4490123456789012344444333664777777777777777777777777777	2.0916 0.99736 1.99736 1.99736 1.99736 1.99355 1.99857 1.99857 1.98856 1.887776 1.77680 1.887776 1.77680 1.66778 1.6778

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6.5897 8.1765 9.0215 9.4216 9.5064 9.3440 8.9719 8.4073 7.6496 6.6750 5.4125	10.4024 12.8658 14.3543 15.2781 15.8236 16.0939 16.1530 16.0429 15.7924 15.4217 14.9448 14.3714 13.7074 12.1814 10.1451 8.9878 7.6751 6.1331	12.8128 16.1030 18.1027 19.3887 20.2137 20.2137 20.9731 21.0459 20.9707 20.4686 19.0697 18.4661 17.8037 11.5.4702 14.5795 13.6291 11.5286 19.0941 7.6977 6.1101	15.7979 19.3979 19.
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M1	XMIN	Y(M2V*)	THETA 8.49133 87.49133 87.49133 87.49133 87.49133 87.49133 87.49133 87.49133 77.4913 88.49723 77.4912 88.49723 77.4912 88.49723 77.4912 88.49723 77.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 87.4973 88.4881 88.7973 88.4881 88.7973 88.4881 88.7973 88.4881 88.7973 88.4881 88.7973 88.4881 88.7981 88.4981 88.49	1075207520752974297429742974297419641964196 124692570368146925775207520752974297429742974297419641964196 109999988888887777776666665555555444444333333322222111111111111111	TR21 -2830 -2977 -3054 -210793 -3134 -3134 -3210 -33388 -3478 -3478 -3665 -3765 -3867 -39908 -44193 -44551 -4808 -4551 -5677 -4808 -4551 -56370 -55677 -56836 -1.5682 -56836 -66168 -66516 -66879 -7256 -74449 -76444 -7841 -76444 -7841 -76444 -7841 -76444 -7841 -76444 -7841 -76444 -7841 -76444 -7841 -76444 -7841 -76444 -7841 -76444 -7841 -76444 -7841 -76444 -7841 -76444 -7841 -76448 -8038 -84975 -1.5429 -7066 -6879 -7066 -6879 -7066 -6879 -7066 -6879 -7064 -70644 -7841 -7841 -7841 -7841 -7841 -7841 -7841 -7844 -7841 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7844 -7841 -7844 -7841 -7844 -78
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M1	XMIN	Y(M2V*)     1440     3582     4095     4095     4894     5842     6620     7281     7855     8656     9293     9881     10165     10834     10839     10834     10839     10834     10839     10834     10839     10834     10839     10834     10839     10834     10839     10834     10839     10834     10839     10834     10839     10834     10839     10834     10836     10836     10837     10838     10835     10835     10836     10836     10836     10837     10837     10838     10836     10837     10836     10837     10837     10838     10837     10838     10837     10838     10837     10838     10837     10838     10837     10838     10837     10838     10837	M2	PTR21
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	.7744 .8457 .9135 .9787 1.0417 1.1632 1.2224 1.2808 1.3387 1.3962 1.4536 1.5108	.7302 .8084 .8820 .9522 1.0198 1.0854 1.0854 1.2123 1.2743 1.2743 1.3356 1.3963 1.4579 1.5786 1.6398 1.7626 1.7626
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.0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001	.0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001	.0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001 .0001
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APPENDIX I

M1 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5	1.4214 1.0625 1. 1.4214 1.0625 1. 1.4214 1.0625 1. 1.4214 1.0625 1. 1.4214 1.0625 1. 1.4214 1.0625 1. 1.4214 1.0625 1. 1.4214 1.0625 1. 1.4214 1.0625 1. 1.4214 1.0625 1. 1.4214 1.0625 1. 1.4214 1.0625 1. 1.4214 1.0625 1.	L XMIN 00	XMAX 1.4214 1.4214 1.4214 1.4214 1.4214 1.4214 1.4214 1.4214 1.4214 1.4214 1.4214	X(M2U*) .7100 .7600 .8100 .8600 .9100 .9600 1.0100 1.1100 1.1600 1.2100 1.2600 1.3100 1.3600 1.4100	Y(M2V*) .0505 .1414 .1832 .2084 .2230 .2296 .2294 .2110 .1932 .1697 .1404 .0624 .0125	M2U •6931 •7452 •7977 •8508 •9045 •9588 1•0137 1•0693 1•1257 1•1829 1•2410 1•3604 1•4220 1•4853	M2 •6949 •7579 •8179 •8754 •9313 •9858 1•0927 1•1458 1•1992 1•2531 1•3081 1•3647 1•4235 1•4854	THETA SIGMA 4.0668 85.9413 10.5392 77.9331 12.7454 73.3186 13.6207 69.6361 13.7705 66.4386 13.4511 63.5440 12.7965 60.8561 11.8841 58.3162 10.7610 55.8849 9.4558 53.5335 7.9852 51.2401 6.3572 48.9867 4.5729 46.7580 2.6272 44.5398 .5092 42.3190	PR21 2.3513 2.2564 2.1614 2.0664 1.9714 1.8765 1.7815 1.6865 1.5915 1.4966 1.4016 1.3066 1.2116 1.1167 1.0217	PTR21 •9234 •9336 •9433 •9524 •9609 •9687 •9758 •9873 •9917 •9951 •9976 •9998 1.0000	TR21 1.1686 1.1584 1.1482 1.1378 1.1272 1.1165 1.0943 1.0828 1.0710 1.0587 1.0460 1.0327 1.0186 1.0036
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2.0000000000000000000000000000000000000	1.7728	.6690 1.4948 .67 .6690 1.4948 .77 .6690 1.4948 .87 .6690 1.4948 .87 .6690 1.4948 .97 .6690 1.4948 .97 .6690 1.4948 1.07 .6690 1.4948 1.17 .6690 1.4948 1.17 .6690 1.4948 1.27 .6690 1.4948 1.27 .6690 1.4948 1.37 .6690 1.4948 1.37 .6690 1.4948 1.37 .6690 1.4948 1.37	200       .1677       .7042         200       .2264       .7567         200       .2647       .8096         200       .2910       .8632         200       .3084       .9173         200       .3187       .9721         200       .3210       1.0835         200       .3139       1.1403         200       .3014       1.1979         200       .2834       1.2562         200       .2295       1.3758         200       .1920       1.4372         200       .1447       1.4999	.6527 2.0998 88.6415 .7231 13.1138 80.3445 .7887 16.3863 76.3996 .8508 17.8918 73.3627 .9102 18.4916 70.8080 .9675 18.5315 68.5745 1.0232 18.1867 66.5854 1.0777 17.5567 64.8028 1.1312 16.7012 63.2122 1.1842 15.6572 61.8179 1.2370 14.4460 60.6448 1.2897 13.0781 59.7456 1.3427 11.5541 59.2201 1.3965 9.8633 59.2582 1.4513 7.9762 60.2520 1.5077 5.8168 63.1606 1.5664 3.0796 71.4647	3.8408 3.6946 3.5484 6769 3.4022 3.2560 3.1098 7065 2.9636 7153 2.8173 2.6711 7307 2.5249 2.3787 2.2325 7464 1.7939 1.6477 1.5015 67439	1.5662 1.5518 1.55373 1.5227 1.5080 1.4932 1.4932 1.4477 1.4477 1.44001 1.3835 1.3665 1.3489 1.33112
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M1	XMIN	0710 -2611 -3557 -4242 -4781 -5219 -5334 -7875 -8422 -8975 -8422 -8975 -8422 -8975 -8422 -8975 -6124 -6323 -6479 -6124 -6323 -6479 -6477 -64735 -6723 -6723 -6723 -6723 -6724 -6735 -6714 -6659 -6450 -6572 -6450 -6295 -6103 -5874 -5604 -5292 -4932 -4	M2	PR21 6.7133 6.5310 6.5310 6.3487 6.1664 5.9841 5.8017 5.8017 5.202 5.371 5.2548 5.0725 4.8902 4.7079 4.8902 4.7079 4.5255 4.3432 4.1609 3.7963	TR21888818999998764991.5537991.5535899628837991.5535899628837991.44552443868831.3313991.2264231.4276691.0011.0011.0011.0011.0011.0011.0011.
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2.5	• 5559 1 · 7987	2301 .3113 .6451 .6451 .64576 .4131 .7506 .4131 .477 .4750 .4961 .9689 .5119 .9689 .5229 .5229 .5319 .5319 .5319 .5319 .5319 .53174 .4835 .4613 .4835 .4613 .4835 .4613 .4835 .4613 .4835 .4613 .4835 .4613 .4835 .4613 .4835 .4613 .4835 .4613 .4835 .4613 .4835 .4613 .4835 .4613 .4835 .4613 .48362 .48362 .2055	.5454	6.2947 6.0978 5.9009 5.9009 5.7040 5.5071 5.3102 5.1133 4.9164 4.7195 4.5226 4.3257 4.1288 3.9319 3.7350 3.5381 3.9319 3.7350 3.5381 3.9319 3.7350 3.5381 3.9319 3.7350 3.6020 4.1288 3.9319 3.7350 5.698 3.9319 3.7350 5.698 3.9319 3.7350 5.698 3.9319 3.7350 5.698 3.9319 3.7350 5.698 3.9319 3.7350 5.698 3.9319 3.7350 5.698 3.9319 3.7350 5.698	1.8406 1.8222 1.8036 1.7851 1.7665 1.7478 1.7291 1.6725 1.6535 1.6535 1.6157 1.5764 1.5764 1.5764 1.4531 1.4082 1.4311 1.4083 1.3589

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<ul> <li>7985</li> </ul>	<ul> <li>7092</li> </ul>	• 6472 • 6472	• 5978 • 59778 • 59
1.2524 1.2524 1.2524 1.2524 1.2524 1.2524 1.2524 1.2524 1.2524	1.4100 1.4100 1.4100 1.4100 1.4100 1.4100 1.4100 1.4100 1.4100 1.4100	1.5451 1.5451 1.5451 1.5451 1.5451 1.5451 1.5451 1.5451 1.5451 1.5451 1.5451 1.5451	1.6728 1.6728 1.6728 1.6728 1.6728 1.6728 1.6728 1.6728 1.6728 1.6728 1.6728 1.6728 1.6728 1.6728 1.6728
-8000 -8500 -9000 -9500 1-0500 1-1500 1-1500 1-2000 1-2500	-7100 -7600 -8100 -8600 -9100 -9600 1-0100 1-1100 1-1600 1-2100 1-2600 1-3100 1-3600	.6500 .7000 .7500 .8000 .8500 .9000 .9500 1.0000 1.1500 1.1500 1.2500 1.3500 1.3500 1.4500 1.4500	.6000 .7000 .7500 .8000 .8500 .9500 1.0500 1.1500 1.1500 1.2500 1.3500 1.3500 1.4500 1.5500 1.5500 1.6000 1.6500
•0231 •1263 •1647 •1849 •1929 •1909 •1791 •1562 •1174 •0259	.0208 .1618 .2177 .2533 .2768 .2912 .2981 .2981 .2981 .2987 .2788 .2589 .2309 .1927 .1382	.0450 .1896 .25550 .3319 .33797 .33797 .3817 .3817 .3817 .3817 .3817 .3919 .2060	048354413395498309418013 04835441339549839 044528954983094180 044528954983094189 044528954983094189 044528954983094189 044528954983094189 044528954983094189
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• 3801 • 3838 • 3869 • 3895 • 3915 • 3927 • 3930 • 3925 • 3908 • 3880	.3882 .3943 .4001 .4056 .4107 .4153 .4193 .4227 .4253 .4271 .4279 .4276 .4261 .4231	3955 4117 41195 41195 44197 4418 4416 4418 4416 4418 441	4117 4117 4117 44319 44519 44519 44519 44519 44519 44519 44519 4519
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8.6716 8.3928 7.228 7.8484 7.5740 7.0251 6.4763 6.4019 5.65316 5.1048 4.52810	8.7265 8.7265 8.72616 8.72616 7.96167 7.6618 8.196618 7.96618 6.8019 6.81710 5.28172 4.4223 4.2274 4.2274 4.2274 4.2274 4.2274 4.2274 4.2277 7.8377 7.8377	1616161616272727272727272727272727272727
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•0498 •1377 •1757 •1956 •2031 •1997 •1853 •1573	•0740 •1786 •2316 •2659 •2883 •3017 •3072 •3056 •2968 •2804 •2553 •2192 •1657 •0620	•0761 •2016 •2660 •3099 •3416 •3641 •3793 •3880 •3908 •3793 •3793 •3648 •3156 •2781 •2279 •1544	• 0633 • 2156 • 2907 • 3816 • 4395 • 44596 • 4596 • 46083 • 46083 • 4107 • 4107	•0524 •0524 •37120 •47063 •47063 •512735 •51001 •4706 •512735 •51001 •4706 •512735 •51001 •4706 •512735 •51001 •4706 •512735 •51001 •4706 •51001 •4706 •51001 •4706 •51001 •4706 •51001 •4706 •51001 •4706 •51001 •4706 •51001 •4706 •51001 •4706 •51001 •4706 •51001 •4706 •51001 •4706 •51001 •
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4898       2.0418       .4900         4898       2.0418       .5400         4898       2.0418       .6400         4898       2.0418       .6900         4898       2.0418       .7400         4898       2.0418       .7900         4898       2.0418       .8400         4898       2.0418       .9400         .9900       .9400       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900         .9900       .9900       .9900	4468       2.2382       .4500         55000       .55000         4468       2.2382       .6000         4468       2.2382       .6500         4468       2.2382       .7000         4468       2.2382       .7000         4468       2.2382       .8500         4468       2.2382       .9000         4468       2.2382       .9000         4468       2.2382       1.0000         4468       2.2382       1.0000         4468       2.2382       1.2000         4468       2.2382       1.3000         4468       2.2382       1.5000         4468       2.2382       1.5000         4468       2.2382       1.5000         4468       2.2382       1.5000         4468       2.2382       1.6000         4468       2.2382       1.7000         4468       2.2382       1.7000         4468       2.2382       1.7000         4468       2.2382       1.7000         4468       2.2382       1.7000         4468       2.2382       1.7000         4468       2.2382       1.7000
0194       4724         2739       5237         3803       5756         4575       6281         5186       6814         5688       7353         6109       8452         6464       8452         6764       9013         7016       9582         7016       9582         7394       10743         7526       1336         7687       13798         7687       3169         7718       3169         7718       3798         7616       3798         7516       7797         6443       9223         6443       9223         6443       9957         6443       9957         6443       9957         6443       9957         6445       3035         20704       3845         23845         2453       3845         24674	0757 -3033 -4162 -4995 -5663 -6221 -6695 -7103 -7450 -8021 -8021 -8021 -8244 -8432 -8587 -810 -8244 -8432 -8587 -8803 -8803 -8803 -8803 -8891 -8992 -7913 -7635 -7312 -6940 -6509 -6008 -5417 -7318 -6940 -6509 -6509 -6008 -5417 -73806 -7233 -73806 -7233 -73806 -7233 -73806
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